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Furthering the Science of Ocean Climate Modelling

From Maltrud et al, page 5: Global Ocean Modelling in the Eddying Regime using POP

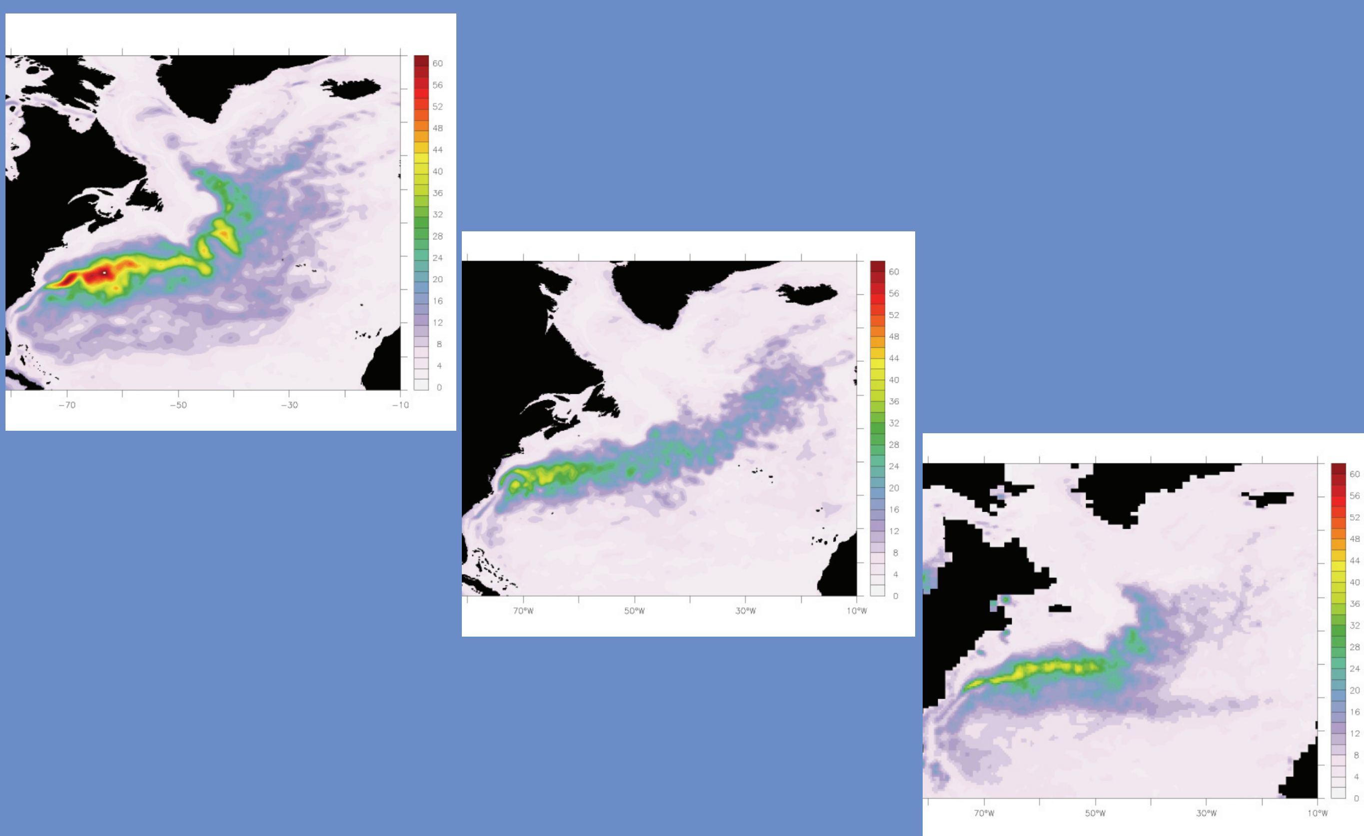

Figure 1. Sea surface height variability (cm) from a) the global 0.1° tripole, b) the global 0.1° dipole, and c) the AVISO altimeter data.

CLIVAR is an international research programme dealing with climate variability and predictability on time-scales from months to centuries. **CLIVAR** is a component of the World Climate Research Programme (WCRP). WCRP is sponsored by the World Meteorological Organization, the International Council for Science and the Intergovernmental Oceanographic Commission of UNESCO.

WCRP World Climate Research Programme

Editorial

I am pleased indeed to have Stephen Griffies Helene Banks and Anna Pirani (ICPO) as co-editors of this issue of Exchanges on "Furthering the science of ocean climate modelling". In part, this edition is a follow-on from Exchanges 42 which focused on Ocean Model Development and Assessment. The edition also provides an article on the activities of CLIVAR's Working Group on Ocean Model Development (WGOMD) following their Workshop and meeting in Bergen last August (see pages 30-32). I would particularly like to welcome Helene Banks as a new Co-Chair of WGOMD alongside the existing Chair, Stephen Griffies. Both they and Anna provide a short introduction to the ocean science aspects of this edition below.

Extreme events is one of the WCRP cross cutting topics which CLIVAR, with GEWEX, has been asked to manage by the Joint Scientific Committee (JSC) for WCRP. Long term multi-year droughts form one aspect of these. The severe drought event that occurred over the Canadian Prairies from 1999-2004/05 is one focus of the GEWEX Worldwide Integrated Study of Extremes (see the link from http://www.meteo.mcgill.ca/wise to the "WEBS follow-on for extremes"). On pages 33-34 of this edition of Exchanges, David Legler, David Gutzler and Sieg Schubert outline current US CLIVAR efforts on drought predictability research, with a request to the international community for participation.

Another important CLIVAR-sponsored activity is the International Climate of the 20th Century Project. The article by Jim Kinter and Chris Folland on pages 34-36 provides both an update on progress and an indication of future directions for the project. The latter are aimed at helping to better understand mechanistic questions relating to seasonal and decadal predictability and forecasting. These outputs will hopefully help in interpretation of the outcomes of both the WCRP/CLIVAR Climate System Historical Forecast Project (www.clivar.org/organization/wgsip/chfp/chfp.php), announced at the WCRP/CLIVAR Seasonal Prediction Workshop in Barcelona in June 2007, and decadal predictability activities which are spinning up under the JSC's decadal predictability cross cut. In terms of decadal prediction, the joint JSC/CLIVAR Working Group on Coupled Modelling and the CLIVAR Working Group on Seasonal to Interannual Prediction are developing plans for coordinated experiments to study multi-decadal prediction and near-term climate change which will draw in other CLIVAR groups also. For example the expertise of CLIVAR's Global Synthesis and Observations Panel in the usefulness of ocean syntheses will be needed for setting initial ocean conditions for such experiments. In addition, the involvement of the wider international community in contributing to these experiments and in proposing diagnostic sub-projects for their analysis will be vital to success overall.

Finally, we also include a short account of the outcomes of the CLIVAR Scientific Steering Group meeting in Geneva last September and the first "GO-SHIP" meeing in November and an update on the WOCE Pacific Ocean Atlas.

One additional happy event at the ICPO has been the birth of a baby boy, Alessandro, to Anna Pirani and her husband Riccardo. Many congratuations to them. Alessandro was 7 lbs 15 oz and 21 inches at birth and is now doing fine, growing and getting used to life at home.

Howard Cattle

Editorial: Furthering the Science of Ocean Climate Modelling

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Ocean models are tools for use in understanding and predicting the ocean. Indeed, models are an essential element for rationally addressing a wide suite of scientific problems. CLIVAR foci requiring sophisticated ocean models include global climate projections, seasonal to decadal prediction, and ocean reanalysis. These areas are key to three of the four CLIVAR objectives. Such high-end applications require a cutting-edge level of science and engineering knowledge, understanding, and creativity to be applied to ocean models to establish the integrity and reliability of the simulations. This work includes developing the algorithms and parameterizations forming the fundamentals of the ocean model; designing model configurations and experiments for addressing scientific questions; efficiently running the numerical experiments on a huge array of computer platforms; and analyzing the computed output in light of an increasing array of observational datasets.

Articles in this edition of CLIVAR Exchanges touch on issues which live in the realm of developing the science of ocean models and of developing experiments to enable scientific questions to be addressed. In particular, some of the articles provide an outline of certain methodologies used in ocean modelling practice. Such information is crucial for the use of the models, though it is often omitted from peer-reviewed papers. Hence, we hope that these articles assist in furthering the science of ocean modelling. This goal follows from our charge as members of the CLIVAR Working Group for Ocean Model Development (WGOMD), in which we aim to facilitate the scientifically rational and robust development and use of ocean models.

More information on the work of WGOMD can be found in this issue's article summarising the meeting held in August 2007, and in the detailed report that will be available on the WGOMD web page (http://www.clivar.org/organization/wgomd/wgomd.php). In particular, as well as holding a workshop on Numerical Methods in Ocean Models, WGOMD discussed the progress of Coordinated Ocean Reference Experiments (CORE), evaluation of ocean models and the future direction of WGOMD.

This edition of CLIVAR Exchanges follows on the heels of the July 2007 edition, which focused on "Ocean Model Development and Assessment," with Peter Killworth as guest editor. Indeed, many of the articles in this edition could readily fit into the July 2007 edition. As such this reflects the healthy state of ocean modelling, in which a huge array of models and applications continue to be considered with an impressive level of realism and integrity.

Parameterizing Submesoscale Physics in Global Climate Models

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Introduction

The ocean is vast and diverse. No computer in the foreseeable future will be able to directly handle the range of scales present in the ocean, yet small-scale phenomena may impact global ocean circulation and climate. The small-scale dynamics of the ocean surface mixed layer are an excellent example, because they are not explicitly resolved by climate models even though they mediate property exchange between the atmosphere and ocean.

The majority of studies of small scales have focused on mesoscale geostrophic eddies (typical scales of a month and 100km) or finescale waves and turbulence (typical lengths up to hundreds of meters and inertial or faster time scales). The range of scales in between the mesoscale and the finescale was considered to be of only secondary importance, perhaps just the tail of the mesoscale spectrum. However, recent work has shown that these scales, the submesoscales, have interesting dynamics and potential climate impact through their actions near the ocean surface. Limited duration ocean-only global simulations with grids fine enough to fairly represent mesoscale eddies are becoming common, e.g., Maltrud and McClean (2005). Eddy-resolving coupled climate models are expected to soon follow, but many decades remain until the submesoscale can be well-resolved in global climate models. Oschlies (2002) demonstrates that the near-surface model fidelity is significantly improved in a regional ocean-only model with 2km horizontal resolution, just brushing into the submesoscale-permitting range. Thus, parameterization of the physics at these scales would benefit modelling for decades to come.

Submesoscale dynamics are dominated by the development of fronts and the ageostrophic circulations associated with the fronts. Observations have shown that near-surface fronts are ubiquitous at all scales larger than the local mixed layer deformation radius, typically a few kilometres (Ferrari and Rudnick, 2000, Hosegood et al., 2006). Recent studies of submesoscale physics have addressed various aspects of frontal dynamics: wind-front interactions (Thomas, 2005), frontogenesis (Lapeyre et al. 2006, Capet et al. 2008), and frontal instabilities (Boccaletti et al. 2007, hereafter BFF). Nice reviews of these results can be found in Thomas et al. (2008) and Mahadevan and Tandon (2006). Thomas and Ferrari (2008) compare the three effects and conclude that they are of similar magnitude for typical oceanic conditions. In all these studies a novel view of the upper ocean emerges, where the depth and stratification of the surface mixed layer is not set by the atmospheric surface fluxes, as currently assumed in all boundary layer theories and parameterizations, but it is radically modified by the ageostrophic circulations that develop at lateral fronts. Fox-Kemper et al. (2008, hereafter FFH) and Fox-Kemper and Ferrari (2008, hereafter FF) derive and validate a parameterization scheme to represent the mixed-layer restratification associated with frontal instabilities and frontogenesis. The dynamics associated with coupling between winds and fronts have not yet been cast in a parameterization.

This note introduces the FFH parameterization. It has been implemented in two global climate models: the Community Climate System Model/Parallel Ocean Program (CCSM/POP2, Smith and Gent, 2002) and the Geophysical Fluid Dynamics Laboratory Coupled Model/Generalized Ocean Layer Dynamics (CM2.2/GOLD, Delworth et al., 2006, Adcroft and Hallberg, 2006). So far, the parameterization has been tested in three contexts: 1) in idealized simulations (FFH and FF), 2) in an ocean-only, 3-degree, 100-year simulation of POP, and 3) in a 20-year 1-degree coupled ocean-atmosphere CM2.2/GOLD simulation. These tests differ greatly. POP is a z-coordinate model with the Large et al. (1994) finescale mixing parameterization, and GOLD is an isopycnal-coordinate model with a refined bulk mixed layer model (Hallberg, 2003). Nonetheless, when the missing physics of frontal instability restratification is approximated by the FFH parameterization, both POP and GOLD show a reduction in model bias when compared to control runs without the parameterization. Future papers will address in more detail the implementation and effects in these global models.

Dynamics of Mixed Layer Eddies

The weak stratification and shallow depth of the mixed layer lead to submesoscale ageostrophic baroclinic instabilities that are trapped within the mixed layer (BFF). FFH dub them mixed layer eddies (MLEs) when they reach finite amplitude. MLEs form by extracting energy from fronts. They have slightly sub-inertial time scales so are fast enough to grow even in the presence of nightly convective mixing. MLEs are submesoscale features with scales near the mixed layer deformation radius (100m to 5km). Satellite (Munk et al., 2001) and in situ (Rudnick, 2001) observations confirm that the ocean is populated with eddies with characteristics consistent with MLE.

Both mesoscale eddies and MLEs drive overturning circulations that act to slump lateral density gradients, converting steep isopycnal surfaces to shallower, wavy ones. The slumping results in a lateral mixing of tracers and in an increase of the vertical density stratification. During slumping lighter water is moved over denser water, and extraction of potential energy results. BFF and FFH show that the slumping and restratification by mixed layer instabilities quickly outpaces restratification by Rossby adjustment (Tandon and Garrett, 1994) and other instabilities (see also Haine and Marshall, 1998).

Since Taylor (1921), eddy diffusivities have been the basic tool to approximate stirring by eddies. Gent and McWilliams (1990, hereafter GM) showed that a similar approach can be taken to represent mesoscale ocean eddies, as long as the lateral diffusion of buoyancy is accompanied by a vertical buoyancy flux acting to release potential energy (e.g., Green, 1970). An eddy-induced velocity streamfunction (see Griffies, 1998, for implementation) can be used to slump density gradients, hence: releasing potential energy and also transporting buoyancy down its mean horizontal gradient to achieve lateral mixing.

FFH follow GM in introducing an eddy-induced overturning streamfunction, but instead of scaling this streamfunction to produce known horizontal mixing (the GM transfer coefficient), they derive a scaling for the streamfunction that achieves the expected release of available potential energy and hence eliminate any dependence on unknown transfer coefficients. The scaling was then tested against a suite of high resolution numerical simulations. The choice to focus on vertical fluxes was motivated by the fact that MLEs rapidly restratify the surface mixed layer through vertical exchanges of buoyancy, while lateral fluxes associated with MLEs are dominated by larger scale motions. Also, it was observed during spin-down of mixed layer fronts by MLEs that the vertical flux is nearly constant while the horizontal flux and diffusivity change dramatically in time. FFH parameterize the submesoscale eddies only, so the parameterization is intended to be used in mesoscale-resolving simulations or in conjunction with a mesoscale parameterization (e.g., GM or a recent improvement, e.g., Ferrari et al., 2008).

The FFH parameterization is cast as an expression for the overturning streamfunction at a front:

$$\mathbf{\Psi} = C_e \frac{H^2 \nabla \overline{b}^z \times \hat{\mathbf{z}}}{|f|} \mu(z)$$

Where H is mixed layer depth, $\overline{b}^z$ is the buoyancy averaged over the mixed layer depth, *f* is the Coriolis parameter and the structure function is

$$\mu(z) = \max \left\{ \left[1 - \left(\frac{2z}{H} + 1 \right)^2 \right] \left[1 + \frac{5}{21} \left(\frac{2z}{H} + 1 \right)^2 \right], 0 \right\}$$

The streamfunction gives an eddy-induced velocity associated with the overturning:

$$\mathbf{u}^* = \nabla \times \mathbf{\Psi}$$

which is used to advect buoyancy and other tracers. The parameterization approximates the eddy fluxes:

$$\overline{\mathbf{u}'b'} \approx \mathbf{\Psi} \times \nabla \overline{b}$$

The form of the parameterization guarantees a down-gradient horizontal flux and an upward, restratifying vertical flux. The scaling found for mixed layer fronts extends to cover the regime of restratification after deep convection, by reproducing the scalings found by Jones and Marshall (1993, 1997) and Haine and Marshall (1998).

Implementation and Impact in Global Climate Models

In a global climate model, the parameterization must be modified. A useful form is,

$$\mathbf{\Psi} = C_e \frac{H^2 \nabla \overline{b}^z \times \hat{\mathbf{z}}}{\sqrt{f^2 + \tau^{-2}}} \mu(z) \frac{\Delta x}{L_f}$$

Introducing the timescale τ, for mixing momentum across the mixed layer (typically a few days) makes the parameterization converge to the subinertial mixed layer approximation (Young, 1994) near the equator. Also, differentiability and finite amplitude are preserved as f goes to zero. The ratio of the grid resolution Δx to the typical scale of mixed layer fronts L_f preserves the average vertical buoyancy flux in the face of weaker buoyancy gradients in coarse-resolution models, which are assumed to have a white spectrum as in models and data (Hallberg & Gnanadesikan, 2006 and Ferrari and Rudnick, 2000). The frontal scale may be either a fixed number, e.g., 5 km, but observations suggest the mixed layer deformation radius (Hosegood et al. 2006).

Since the MLEs tend to restratify the mixed layer, it is not surprising to find that the boundary layer thickness is reduced when the parameterization is introduced (Figure. 1, page 19). Furthermore, the action of the parameterization is most pronounced where mixed layers are deep and horizontal buoyancy gradients are large. These regions are those anticipated by FF by inference from satellite data. The models show qualitatively similar shoaling of the boundary layer in similar regions, but quantitatively different responses to the parameterization. It is likely that the different resolutions of the models contribute significantly, and possibly also the ocean-only versus coupled configurations. In any case, once longer and more directly comparable resolutions and simulations are available a more detailed comparison will follow.

Is a shallower boundary layer or mixed layer more realistic? The POP model provides mixed layer depth as well as boundary layer depth. Figure. 2 shows a comparison to mixed layer climatologies of the time average of the mixed layer depth for years 90-100 of the POP model simulation with the MLE parameterization and the control run without. BMFLI is the de Boyer Montegut et al. (2004) temperature-based mixed layer climatology and Levitus is the Monterey and Levitus (1997) climatology. Figure. 2 shows a probability distribution of finding a given difference between the model time-mean and the climatology at an arbitrary location. It is clear that the change induced by the parameterization is larger than the difference between climatologies, and that the control run is biased toward deep mixed layers. Introducing the parameterization reduces this bias: the rms error is reduced from about 15m to 7m, and the skewness (indicating bias) is reduced from 2.4 to 0.6.

Conclusions

A new parameterization for restratification by mixed layer eddies is introduced. The parameterization was shown to be effective in idealized simulations by FFH and FF. It has now been included in CCSM/POP and CM2.2/GOLD and this note demonstrates that it reduces bias over control runs in preliminary simulations.

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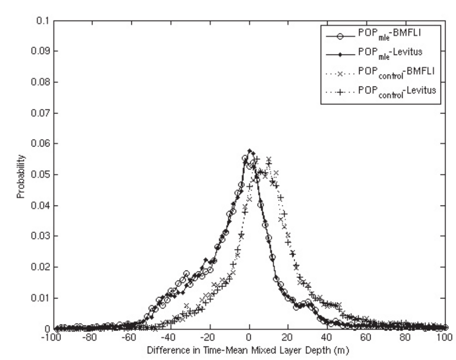

Fig. 2: Probability distributions of difference between modeled time-mean mixed layer depth and observed time-mean mixed layer depth. POP model with MLE parameterization and the POP control run are compared to BMFLI and Levitus mixed layer depth climatologies. (Bin width of 2m).

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Global Ocean Modeling in the Eddying Regime Using POP

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Introduction

The Parallel Ocean Program (POP) was developed at the Los Alamos National Laboratory (LANL) in the early 1990's for use on high performance parallel computers (Dukowicz, et al., 1993). Early emphasis was on performing simulations requiring computational capability beyond that accessible with other codes. The combination of algorithmic improvements and access to powerful hardware led to simulation of ocean circulation in the eddying regime being a major goal of early and ongoing Department of Energy ocean modelling activities at LANL.

Expanding on the ground breaking high resolution simulations of Semtner and Chervin (1988), POP was used in a series of near global (including all but the Arctic) ocean simulations at 0.28° horizontal resolution[1] (Maltrud et al. 1998). These simulations showed broad agreement in the geographical distribution of mesoscale eddy variability with altimeter observations (Fu and Smith, 1996; McClean et al, 1997), but underestimated eddy amplitudes at shorter wavelengths and periods, and misrepresented smaller scale features of the time mean flow such as the path of the Gulf Stream and Kuroshio. These global runs were followed by 0.1° North Atlantic simulations (which extended from 20S to 78N) that, for the first time, used grid cells smaller than the first baroclinic Rossby radius throughout the domain in a fully thermodynamic, realistic basin scale setting (Smith et al. 2000). These experiments at resolutions of 10km and finer suggested that a regime shift had been reached, as both eddy and mean flow quantities (such as the Gulf Stream separation) much more closely resembled observations. The

[1] *Resolution will be denoted by the equatorial longitudinal spacing*

success of the 0.1° POP North Atlantic experiments inspired the first fully global 0.1° simulation (including the Arctic) by Maltrud and McClean (2005). This article describes some lessons learned in performing these large simulations, and presents examples of our current high resolution modelling efforts.

Model Configuration

POP is descended from the Bryan-Cox-Semtner lineage of geopotential coordinate ("z-level") models (Griffies, 2004) formulated on the Arakawa B-grid and using leapfrog time stepping. Important improvements were introduced in the POP code, including the surface pressure and implicit free-surface solution of the barotropic mode (Dukowicz and Smith, (1994)) and formulation of the equations on a general orthogonal grid. Along with its ability to run efficiently on parallel computers, POP established a significant user base, including being selected as the ocean component of the NCAR Community Climate System Model (Kiehl and Gent, 2004; Collins et al, 2006).

The general orthogonal grid formulation has been especially useful for including the Arctic while avoiding the pole singularity and eliminating the necessity of filtering at high latitudes of the latitude-longitude grid. Until recently, we have used a 'displaced-pole' grid where the North Pole of the grid is smoothly shifted into land (e.g., Canada in Maltrud and McClean (2005) and Greenland for the CCSM configuration (Yeager et al, (2006)) in a manner that preserves second order accuracy of the spatial discretizations. More recently, we have begun using a tripole grid which in effect splits the polar singularity in half and moves each half into opposing land masses (e.g., Canada and Russia). Note that the Southern Hemisphere (since there is land at the south pole) and the Northern Hemisphere tropics (in order to have the grid aligned with the equatorial wave guide and dominant zonal flows) remain on a latitude-longitude grid.

One drawback of the dipole grids is that grid cell aspect ratios can be fairly large (e.g., 9% of the ocean cells in Maltrud and McClean (2005) had a ratio greater than 2). In addition to presenting truncation errors which are much larger in one direction than the other, very thin cells can severely reduce the model's time step via CFL limitations, requiring explicit modification of the diffusion coefficients in these areas to allow a reasonably large time step.

The relationship of vertical to horizontal resolution has not been systematically studied in the eddying regime. Vertical resolution should be relatively high near the surface to aid in the simulation of mixed layer processes. Level thicknesses should be chosen to increase smoothly in order to preserve accuracy. These criteria, however, are no different than those applied to non-eddy-resolving models. Issues that are specific to a strongly eddying regime have only begun to be explored (see, for instance, Danioux et al. (2007)).

One major advantage of the free surface formulation in POP is removing the need to smooth the model bathymetry as was required by the streamfunction formulation used by its predecessors. Consequently the 0.28° and 0.1° dipole grids were prepared without smoothing. However, topographic roughness at the grid scale can induce very strong vertical velocities, which in turn can give rise to excess grid-scale dissipation. A partial bottom cell (PBC) representation of topography has been shown to improve the representation of topographic interactions, and reduce grid-scale noise (Pacanowski and Gnanadesikan (1998)). In our most recent 0.1° tripole experiments, we have adopted the PBC representation of topography, and used a smoothing interpolant in the preparation of the discrete topography. Some hand editing of topography is typically still required. While the depth of sills and the width of passages require less alteration than at lower resolutions, the greater complexity of the topography presents additional features which may require attention.

Since one goal of eddying simulations is to allow the flow to evolve with the minimum amount of artificial diffusion possible, we have typically used a biharmonic form for the diffusive terms in both the momentum and tracer equations, since this moves the dominant dissipation scale to higher wave numbers than for the Laplacian form. In addition, we also decrease the diffusion coefficients as the grid size gets smaller. For example, if one equates the grid scale advective and diffusive time scales, the diffusion coefficients scale with the grid area to the 3/2 power (Maltrud et al (1998)).

With explicit mesoscale eddies in these simulations, it was hoped that the precise form of the diffusive terms (which act as a model for eddy processes in coarser resolution climate models) wouldn't matter very much, as long they were large enough to dissipate grid scale noise and resolve the Munk layer near boundaries. Chassignet and Garraffo (2001) and Bryan et al (2007) show that this is not the case, and the choice of lateral dissipation remains critical (see Hecht et al. (2008) for a review of the issue). Smith and Gent (2004) demonstrate improvements when using an adiabatic closure for tracer mixing in the eddying regime, but at a substantial computational price. Hunke et al (2007) show that scaling of coefficients with the grid scale for both biharmonic and aplacian forms is crucial for high latitudes

Starting a run from an initial condition derived from observational data (such as the World Ocean Atlas) can introduce issues not experienced at coarser resolutions. The process of geostrophic adjustment can generate currents and waves that cause the simulation to go numerically unstable. We have had to start 0.1° simulations with a time step as small as a few seconds to get through this initial adjustment phase (5-10 model days), compared to an 8-10 minute time step for the subsequent period. Often, we will also turn off surface forcing during this initial phase so other possible fast modes are not introduced into the system. At resolutions coarser than 0.1° (but still eddying), diffusion and slower currents apparently mitigate this problem to large degree.

Some data sets may be gravitationally unstable in various locations when using the model's equation of state, which causes a strong response in any hydrostatic model. In POP, either convective adjustment or very strong vertical diffusion (1000 cm^2/s) is used to make the water column stable. As a result, adjacent columns can develop very high horizontal gradients if one of them has been convected very deeply. Note that 'stabilizing' an initial condition before starting the model leads to the same problem unless strong horizontal smoothing is also applied. In the end, using a very small time step for several days appears to be an adequate solution.

Most of the surface forcing issues are similar to those associated with lower resolution models, with a few exceptions. Jayne and Tokmakian (1997) showed that discontinuous daily forcing can excite spurious inertial oscillations which can be removed with temporal interpolation. In general, one must also be mindful of the large difference in spatial scales between the atmospheric reanalysis products typically used for creating surface forcing and the ocean model grid. This can be very important near coastlines, especially for wind stress and fresh water fluxes.

Testing at lower resolution (e.g., 0.4° tests for a 0.1° setup) or with basin scale configurations at the same resolution (e.g., 0.1°

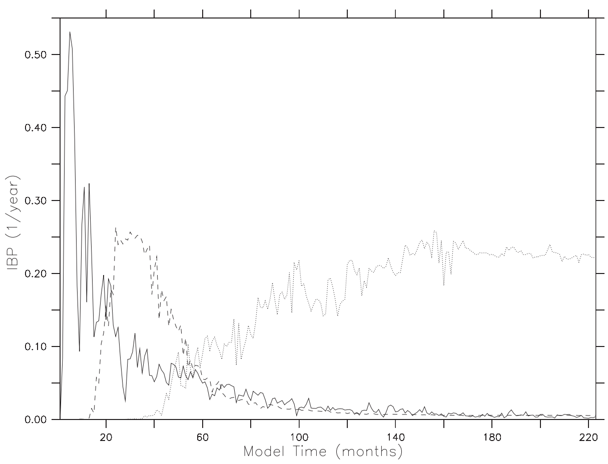

Figure 2: Time series of the global IBP at 3 locations: Pacific Subtropical Mode Water at 150ºE, 35ºN, 300m (solid), Circumpolar Water at 40ºW, 45ºS, 500m (dashed) and Atlantic Deep Water at 52ºW, 10ºN, 2500m (dotted, which has been multiplied by 10 for clarity).

NA for 0.1º global run) can be very useful. However, there are caveats in addition to the expected drop in eddy energy due to decreased resolution, for example. We have seen a very good simulation of the Equatorial Undercurrent in a 0.4º global model deteriorate significantly at 0.1º using the exact same forcing, presumably due to the less diffusive nature of the higher resolution case. Artificial boundaries in basin models can also have significant effects. We extracted the North Atlantic sector (from 20ºS to 78ºN) of the Maltrud and McClean (2005) global grid and applied the same forcing, and the representation of the Gulf Stream improved dramatically compared to the fully global domain, with a strong Northwest Corner and realistic Gulf Stream separation.

Results from the new 0.1º tripole model

As successful as the 0.1º dipole run of Maltrud and McClean (2005) was, there were also some problems. Most conspicuously, the Gulf Stream reverted back to the less-realistic behaviour typically seen at lower resolution, unlike the 0.1º North Atlantic run. In particular, the separation was north of Cape Hatteras and the North Atlantic Current failed to turn back to the northwest around the Grand Banks. In hopes of correcting these biases, we configured a new 0.1º model with the addition of PBCs on the tripole grid. At the time of this writing, this new simulation has run 34 years using a repeating annual cycle of monthly averaged forcing. Figure 1 (front cover) shows the North Atlantic sea surface height variability from the 0.1º tripole run compared to the 0.1º dipole run and the AVISO gridded altimeter data. Clearly the new simulation has corrected the Northwest Corner bias and (less obviously) improved the separation point. However, it does appear that now there may, in fact, be too much variability.

In order to enhance our understanding of turbulence and transport in eddying models, we have added a dozen passive tracers to the current simulation. Following the work of Peacock and Maltrud (2006) using a 3º version of POP, a suite of Impulse Boundary Propagators (IBPs) are being simulated. A useful property of IBPs is that they give an approximate probability density function of ventilation times, i.e., the transit time distribution (TTD) at a given location (Figure 2). Our intention is to use the IBP simulated by the eddy resolving model as a metric in evaluating eddy parameterizations used in coarser resolution models such as the CCSM. As complements to the IBPs, CFC-11 and a suite of float deployments are also being simulated to assess the fidelity of the solution.

Conclusion

From POP's inception, the goal of our effort has been a better understanding of ocean circulation and its role in the climate. We feel eddying ocean models will play a crucial role in future climate projection by explicitly simulating eddies, resolving important small scale topographic and flow features, and more accurately simulating transport and ventilation processes.

While great progress has been made in optimizing the model code itself to run efficiently on computer systems with 10,000 processors or more, there remain significant challenges in realizing century time-scale coupled climate simulations with an eddy-resolving ocean component. Analysis tools, and computational and storage systems available for post-processing of model output have not kept pace with the systems used for the simulation itself. In addition, the demands on human resources expand many-fold with higher resolution simulations. The level of detail in the solutions, and the enhanced level of variability, and the resource consequences of errors require many people looking early and often at the results, as well as the forcing fields, initial conditions, and most other aspects of the model setup.

Acknowledgements

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Impact of relative atmosphere–ocean resolution on coupled climate models

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Introduction

There are many examples of ocean processes that are important for climate simulation and which require some minimal mesh size for a believable simulation (examples include dense flow through narrow gaps, boundary currents, deep water formation, eddy processes involved in Tropical Instability Waves, Agulhas rings and the Antarctic Circumpolar Current). However, when considering the fidelity of climate models, we cannot only consider ocean model resolution; if atmospheric mesh size is insufficient to distinguish important oceanic features, then important coupling and feedback effects may be excluded. Such a situation was found by Roberts et al. (2004), in which a 1/3 degree resolution ocean model was coupled to a 280km atmosphere model. The ocean simulation is hugely improved (compared to an ocean model with 1.25° spacing), but there are rather few changes to the large-scale atmospheric and climate simulation.

Hence we need to consider the correct balance between atmospheric and oceanic mesh sizes, so that the most important processes are captured in both components, in addition to the necessary coupling and feedbacks. The purpose of this article is to show several examples where increases in ocean model resolution also require increases in atmosphere resolution in order for the coupled effect to be properly realised.

Models

The joint DEFRA/NERC-funded UK-Japan Climate Collaboration (UJCC) project, together with the NCAS-Climate UK-HiGEM project (Norton et al., 2007), have been developing coupled models based on the Met Office Hadley Centre's HadGEM1 model (Johns et al., 2006, a configuration of the Met Office Unified ModelTM(UK)), but with enhanced resolution. Using atmospheric models with 150km, 90km and 60km mesh sizes at mid-latitudes, and ocean models at 1 degree (with enhancement to 1/3 degree meridionally at the equator) and 1/3 degree, we have formed a matrix of models in which we can attempt to understand the relative importance of model resolution in a coupled framework (in a similar way to the Japanese CCSR/NIES/FRCGC groups with their MIROC3.2 coupled model (Hasumi and Emori, 2004) using T42, T106 and T213 atmosphere models and 1.4 degree and 0.25 degree ocean models). Integrating such models for 50-100 years has been made possible through use of the Japanese Earth Simulator super computer. Here we describe results from versions of the coupled HadGEM model (150km atmosphere, 1-1/3 degree ocean) and HiGEM model (90km atmosphere, 1/3 degree ocean) as well as the intermediate models.

Results

The impact of model resolution in the coupled framework can take various forms. Examples will be shown which illustrate: (a) strong local feedbacks between atmosphere and ocean as mesh size is reduced, leading to changes in the coupling of the components and potential changes to the mean state, and (b) internal ocean processes at higher resolution changing the mean ocean climate, which therefore changes the forcing to the atmosphere.

Tropical Instability Waves

Tropical instability waves (TIWs) in the eastern tropical Pacific Ocean, caused by mixed barotropic/baroclinic instability, are a highly visible sign of ocean variability in observations (e.g., Legeckis, 1977). They are often poorly represented in climate models as, although their zonal wavelength is large (1000-2000 km), the cusp of the wave is very narrow. Hence the wave breaking (the movement of cold water off the equator, and warm water onto the equator) only begins to be represented with ocean model mesh sizes of about 1 degree. The SST change across a TIW can also be large (2-5C), and hence a high resolution atmosphere is needed to resolve the SST gradients.

The impact of improved TIW representation in a coupled model is illustrated in Figure 1. The wind stress divergence field is shown for both HadGEM and HiGEM, and overlaid are the associated SST contours depicting the characteristic TIWs. It has been shown that perturbations in the wind stress divergence and curl fields are linearly related to the underlying SST gradient in the eastern equatorial Pacific (Chelton et al., 2001). Changes in SSTs are thought to modify the overlying wind field via alterations in the stability of the Atmospheric Boundary Layer (ABL) and local sea level pressure (Hayes et al., 1989). Both models resolve the oceanic TIW signature, though stronger and earlier in HiGEM with its higher zonal resolution. However, the low resolution HadGEM atmosphere is unable to capture the SST perturbed wind field on the length scales of the TIWs. The TIW perturbed wind field is apparent in HiGEM as patches of high wind stress divergence, indicated by white shading, associated with the cusp-like features of the SST contours.

Chelton et al. (2001) describes two measures of ocean-atmosphere coupling in relation to TIWs. In the first, the degree of coupling, can be derived from the amplitude of the cosine (sine) dependencies that the wind stress divergence (curl) has on the angle between the SST gradient and wind vectors on TIW length scales. In the second, the strength of coupling, is defined as the slope of fit between the downwind (crosswind) SST gradient and wind stress divergence (curl) on TIW length scales. With higher horizontal resolution in both ocean and atmosphere, HiGEM has a significantly greater degree and strength of coupling than HadGEM. However, the degree and strength of coupling is still less than that derived from satellite observations by Chelton et al. (2001). This deficiency may be accounted for by increasing the resolution yet further or it may suggest that the model is not resolving the physics of the system completely. If we degrade the resolution of the SSTs to that of the atmospheric model in HiGEM, we increase the strength of the coupling (i.e. grad(SST) is weakened thus strengthening the slope d(grad. tau) / d(grad SST)) although the degree of coupling remains relatively unaffected. By analogy, if we increase the resolution of the atmosphere in HiGEM to that of the ocean grid we are likely to resolve sharper features in the ABL, thus increasing not only the strength of coupling, but also the degree of coupling on the length scales of the TIWs.

By improving TIW representation in coupled models through refinement of the horizontal resolution (including the convergence of ocean and atmosphere mesh size) we will better resolve the effects of the TIWs on the ABL. Such a modification may manifest itself locally through, for example, cloud distribution in the eastern equatorial Pacific (Deser et al., 1993) or through an influence on the mean climate of the tropical Pacific Ocean. An illustration of the latter is described in Roberts et al. (2004), in which the ocean resolution in a coupled model is increased to resolve TIWs. It was found that the SST bias present in the model was significantly reduced, and this was shown to be due to the explicit representation of TIWs as an advective process, in which they remove cold water from the equator and replace it with warmer water from off the equator. The refinement in the SST field results in an improvement to the atmospheric winds, which in turn leads to a better simulation of the whole zonal atmospheric Walker circulation (Roberts et al., 2008). It has also been suggested that the modified ABL may feedback onto the TIWs themselves (Pezzi et al., 2004). There are many other regions where such small-scale interactions may be important to properly simulate large-scale climate (e.g. Agulhas retroflection; O'Neill et al., 2003).

Coastal effects

Coupled climate models often suffer from large biases in regions adjacent to coastlines, most prominently off the eastern boundaries of Africa and America, where complex interactions between atmospheric winds and clouds, and ocean upwelling and SST, are poorly simulated. Although these areas only occupy 0.5% of the global ocean, they account for 11% of the global primary production transported to the thermocline and 20% of global fish catch (Kearns and Carr, 2003), and hence are an important part of the carbon cycle and our food supply. Observations show that these regions are very sensitive to climate change (McGregor et al., 2007).

The impact of ocean and atmosphere mesh size on the seasonal cycle of SST in a 3x3 degree area along the North African coast, centred on 30N, 11W, is shown in Figure 2 (page 10). The thick line is based on Reynolds SST observations from 2001-2006 (Reynolds et al., 2002), and model data from the different resolution coupled models averaged over 20 years. While HadGEM shows significant but opposite-signed biases in summer and winter, the HiGEM model follows the observations more closely. Although a higher resolution in either the atmosphere or the ocean improves the simulation, both are clearly needed to give a good simulation throughout the year. The increased atmospheric resolution improves the processes that determine the radiation balance over these stratocumulus areas in summer, while the ocean resolution probably moderates the seasonal cycle through a stronger upwelling response which is important throughout the year.

Hawaiian Lee Countercurrent

Another illustration of the incremental role that ocean and atmosphere mesh size can play on the coupled climate is seen in the simulation of the Hawaiian Lee Countercurrent (HLCC), which is described in detail by Sasaki and Nonaka (2006). Simply stated, a wind stress curl caused by the trade winds interacting with the Hawaiian Islands induces a circulation in the ocean which drives a eastward countercurrent at about 20N extending from west of 160E to the Hawaiian Islands. It is thought that interaction and feedbacks between atmospheric wind stress curl and ocean SSTs and currents cause the HLCC to stretch such a distance.

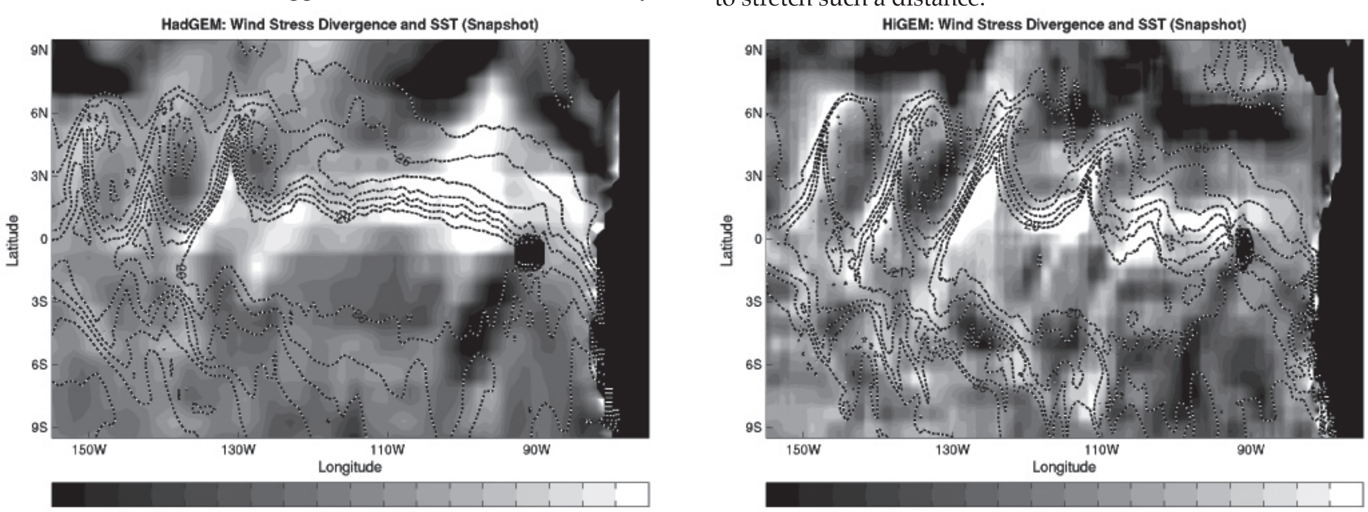

Figure 1: Atmospheric boundary layer response to Tropical Instability Waves in the ocean. Daily mean windstress divergence (Nm-2 x 10-7, shading) and daily mean sea surface temperature (black and white dashed contours, 20C to 26C every 1C) for a) HadGEM and b) HiGEM. Daily mean fields taken from the 13th and 5th September of the HadGEM and HiGEM runs respectively.

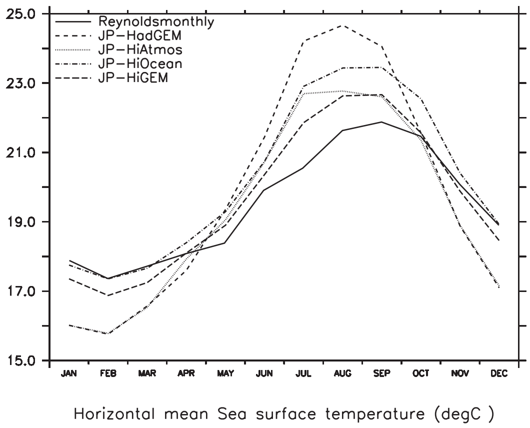

Figure 2: Seasonal cycle of SST (degree C) averaged over a 3x3 box centred on 30N, 11W along the North African coast. Solid line is Reynolds 2001-2006 observations (Reynolds et al., 2007), short dashes for the lowest resolution coupled model (HadGEM), dots for a higher resolution atmosphere, dash-dots for a higher resolution ocean, and long dashes for both high resolution atmosphere and ocean (HiGEM). All model data has been averaged over 20 years.

Using the model matrix, the relative roles of atmosphere and ocean for inducing this current can be studied. Figure 3 (page 19) shows the wind stress curl (colours) and the ocean zonal current at 35m (contours) for the four coupled models. In the low resolution HadGEM model (a), there is strong local wind stress curl over the Hawaiian Islands, and a weak zonal current. With higher resolution atmosphere (b), the wind stress curl signal stretches further west, as does the current. The higher resolution ocean with low resolution atmosphere (c) shows a current which stretches over to 160E and beyond, but with relatively modest wind stress curl, while (d) shows the high resolution coupled response, with the local maximum in wind stress curl collocating with the stronger ocean current over to 160E. Such changes to the circulation cause a warming of the local SSTs, which may be related to local changes in clouds and precipitation.

The Hawaiian Lee Countercurrent is a simple example of how higher resolution atmosphere and ocean components can lead to changes in simulated circulation. It may well be that changes to the persistent small-scale wind stress curl features (when comparing within the model matrix) found in many other regions (particularly over the Southern Ocean and boundary currents) might also lead to changes in their simulation and behaviour, but these will require more detailed analysis.

Discussion

There are many important interactions between the atmosphere and the ocean occurring on small time and space scales, and it is a challenge to represent the most important of these processes in our climate models. Systematic studies of the impact of model resolution on simulated coupled climate are a useful first step, but other methods of analysis will also be needed to isolate and identify individual processes.

For example, UJCC has performed experiments with a variety of atmosphere model resolutions, using AMIP-II SST and sea-ice forcing (Gates et al., 1999) which is nominally 1° resolution but is effectively much smoother than this in time and space. Surprisingly few differences have been found between these simulations, and it is reasonable to ask whether using such smooth forcing is partly to blame. Experiments in which higher resolution ocean SSTs have been used to force atmosphere models (e.g. Chelton et al., 2005) suggest that this can make a significant difference to model variability, and hence the development of higher resolution SST datasets (for example the Reynolds and OSTIA datasets; Reynolds et al., 2007, Stark et al., 2007) will be important tools for future experiments, particularly as atmosphere model resolution increases.

While it is clearly desirable to continue to develop higher resolution ocean models, since there are many important processes that are not properly simulated in the current generation of models, continued thought must be given to the most appropriate resolution of forcing (be it from observations or coupled to an atmospheric model) in order that the feedbacks and interactions are also represented.

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Further information on UJCC and UK-HiGEM projects can be found at http://www.earthsimulator.org.uk/index.php and http://www.higem.nerc.ac.uk/

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Development of a global ocean model with the resolution of 1°×1/2° and 1/8°×1/12°

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1. Introduction

Ocean general circulation models (OGCMs) have become more and more complex and sophisticated during past decades. The present OGCMs can be used to address various purposes such as global warming projection, seasonal prediction, and the carbon cycle, but it is hard to design and maintain global models for each different purpose. The Meteorological Research Institute (MRI) of the Japan Meteorological Agency is developing a baseline global OGCM to meet these needs.

The resolution of our base-line model is set to 1°×0.5°. Since mesoscale eddies and swift western boundary currents are not reproduced in such a low resolution model, it is important to evaluate the representation error caused by this insufficient resolution. At the same time, it is necessary to assess the fundamental limitations of the model that are not overcome by increasing horizontal resolution.

This article presents the assessment of the upper ocean circulation. The representation issues are assessed by comparing with a global eddy-resolving model and the fundamental issues related to changing surface forcings are also addressed.

2. Model

The Meteorological Research Institute Community Ocean Model (MRI.COM) (Ishikawa et al., 2005, Tsujino et al., 2006, Hirabara et al., 2007) is used. Its basic characteristics are listed in Table 1. Here we describe some unique techniques used in MRI.COM to run global models. It uses an Arakawa B grid, and coastlines are created by connecting tracer points instead of velocity points. This is useful for coarse-resolution global models because a narrow passage can be represented by one velocity cell. A split-explicit algorithm is used for the barotropic and baroclinic part of the equations. The vertical coordinate near the surface follows the surface topography like sigma-coordinate models (Hasumi, 2006), enabling us to adopt a fine-vertical resolution near the surface without causing a vanishing of the uppermost layers in the southern ocean, where sea surface height is significantly lower than other regions.

Table 1: Features of MRI.COM

Grid arrangement (Horizontal)	Arakawa B (coastline is on the tracer point)
Grid arrangement (Verical)	Z-level + Parial cell at the lowest level Bottom Boundary Layer (option)
Free-surface	Explicit (Killworth et al., 1991)
Momentum advection	Quassi-enstrophy conservation scheme (Ishizaki and Motoi, 1999)
Tracer advection	UTOPIA and QUICKEST
Sea Ice model (Thermodynamics) (Dynamics)	 Mellor and Kantha (1989) Hunke and Ducowicz (2002)

3. Experimental design

In this article we show three experiments differing mainly in horizontal resolutions and forcings: coarse-CORE run, coarse-JRA run, and fine-JRA run,. Basic settings are summarized in Table 2. The tripolar grid is chosen. The resolution of the fine-JRA is set to 1/8°×1/12°, which is the necessary resolution to represent the Kuroshio Extension (Tsujino and Fujii, 2007). The topography of the coarse-resolution model is modified to represent the important current systems. Preliminary results of the fine-resolution model benefit from this modification around complex archipelagos such as the Philippines Islands.

For the coarse-CORE run, the model is driven by the surface forcing data of the Co-ordinated Ocean-Ice Reference Experiments (COREs) (Large and Yeager, 2004). For the coarse-JRA and fine-JRA run, the coarse- and fine-resolution models are driven by the climatological monthly forcings derived from the dataset of the Japanese 25-year Reanalysis Project (JRA25) (Onogi et al., 2007). JRA25 provides surface fields as other major reanalyses. It has been reported that JRA25 is in general comparable to ERA and NCEP (e.g., Zhao and Li, 2006).

The initial conditions of the coarser resolution model are derived from the 0.25° version of World Ocean Atlas 2001 (WOA01) and the Polar Science Center Hydrographic Climatology (PHC), which is also used for the restoring of the sea surface salinity. The coarse resolution model is integrated for 50 years to spin-up the wind-driven circulation. The result of year 40 of the coarse-JRA run is interpolated and used as the initial conditions of the fine-JRA run. The integration time of fine-JRA run is 10 years.

Starting from the Sverdrup balanced states, the Kuroshio Extension and the Gulf Stream emerge accompanying the recirculation gyres within 3 years in the subtropical gyres of the fine-JRA run. The dynamical setup of these currents is finished within about 6 years, which is much faster than starting from the observations. The improvement in the tracer distribution occurs in the upper layer even during this short integration. This is consistent with the study of western boundary currents using the "ideal settings" (Nakano et al. 2008). This method helps to estimate the impact of the resolution.

Grid	Tripolar grid (Singularities of bipolar grid is (64°N,80°E) and (64°N,100°W)
Resolution (Coarse resolution)	1°(zonal), 1/2° (meridional), 50 levels + BBL (Nakano and Suginohara, 2002) (Total 364×368×51)
Resolution (Fine resolution)	1/8°(zonal), 1/12° (meridional), 50 levels. (2884×2152×50)
Thickness of vertical grid	4, 5, 6.5, 7.5, 9, 11.5, 14, 16, 17.5, 18, 18.5, 20, 20.5, 21, 22, 23, 24, 27, 30, 30, 35, 40, 40, 50, 60, 65, 70, 75, 80, 90, 100, 100, 125, 150, 150, 150, 175, 225, 250, 250, 250, 275, 300, 300, 300, 300, 300, 450, 600, 600 (m)
Surface forcing (1) for Coarse-JRA run and Fine-JRA run	Climatological data set derived from Japanese 25 year Reanalysis Project (JRA25) and a bulk formula of Kara et al. (2000).
Surface forcing (2) for Coarse-CORE run	Climatological data set for Co-ordinated Ocean-Ice Reference Experiments (CORE).
Salinity restore	8 days for uppermost 4 m.
Normalized hydrology	No
Horizontal diffusion Parameterization Horizontal viscosity (Coarse resolution)	Harmonic isopycnal diffusion (coef.= $5x10^2$ m^2s^{-1}) + GM-parameterization (coef.=$5x10^2 m^2s^{-1}$). Harmonic Smagorinsky-like viscosity
Horizontal diffusion Horizontal viscosity (Fine resolution)	Bi-harmonic diffusion (coef. = $1x10^8$ m^4s^{-1}) Biharmonic Smagorinsky-like viscosity
Mixed layer model	Noh and Kim (1999)
Background viscosity and diffusion	Tidally driven mixing over rough topography (St. Laurent et al., 2002)
Initial state (Coarse resolution)	WOA01(south of 64°N) + PHC (north of 64°N) Integration: year 1 – year 50
Initial state (Fine resolution)	End of year 40 of coarse-JRA run Integration: year 41 – year 50

Table 2: Setting of the global ocean simulations

4. Results

Figure 1 (page 19) shows the biases of the annual mean sea surface temperature of the last two years of the runs. The patterns are in general very similar. Notable differences are seen between CORE and JRA runs in the regions of upwelling caused by the local winds. The warm bias off the western coast of the continents (California, Ecuador, Chile, Angola) and the cold bias in the central Pacific are seen in limited areas near the coast and along equator in the JRA run, but these biases are broader in CORE run. They are presumably due to the difference in the resolution of the wind-forcing data; the resolutions of CORE and JRA are T62 and T106, respectively.

Figure 2 (page 20) shows the difference in the barotropic stream function between the fine-JRA and coarse-JRA runs. The largest differences are found in the western boundary and the Southern Ocean, where the effect of the meso-scale eddies is considered to be large. The currents in these regions are in general more realistic, leading to reduced bias in these regions in the fine-JRA run (Figure 1). Bias in equatorial region is quite similar despite the presence of Tropical Instability Waves and many complicated currents reproduced in the fine-JRA run. The cold and warm biases in the interior of the subtropical and subpolar gyres are not reduced by the increase in resolution.

The differences between the experiments are more conspicuous in the subsurface than at the surface. A Taylor diagram shows that biases are reduced in the fine-JRA run in both the temperature and salinity fields (Figure 3). This improvement is in large part related to the improved representation of water mass transport around the recirculation gyres in the subtropics.

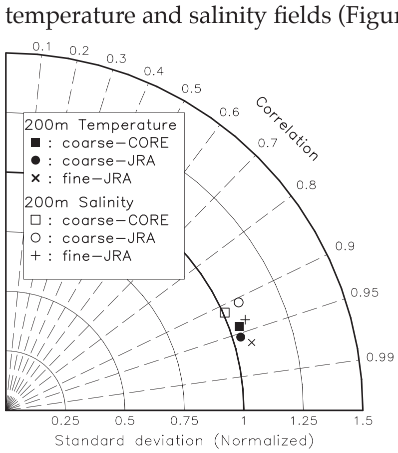

Figure 3: Taylor diagram for temperature and salinity at 200 m from 40°S to 50°N.

5. Summary

Sensitivity experiments on the MRI.COM global model using different surface forcing data and resolutions are conducted. The biases of SST are within 1°C in large part of the oceans but the equatorial cold bias and the eastern boundary warm bias are found for all cases. The improvement by increased horizontal resolution is significant near the western boundary currents and recirculations of the subtropical gyres. The model settings will be fixed through further analyses including analysis of the thermohaline circulation.

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The MITgcm/ECCO adjoint modelling infrastructure

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Introduction

The availability of an adjoint model as a powerful research tool complementary to an ocean model was a major design requirement early on in the development of the MIT general circulation model (MITgcm) (Marshall et al., 1997, Marotzke et al., 1999, Adcroft et al., 2002). It was recognized that the adjoint permitted very efficient computation of gradients of various scalar-valued model diagnostics, norms or, generally, objective functions with respect to external or independent parameters. Such gradients arise in at least two major contexts. If the objective function is the sum of squared model vs. observation differences weighted by, e.g., the inverse error covariances, the gradient of the objective function can be used to optimize this measure of model vs. data misfit in a least-squares sense. One is then solving a problem of statistical state estimation. If the objective function is a key oceanographic quantity such as meridional heat or volume transport, ocean heat content, or mean surface temperature index, the gradient provides simultaneously a complete set of sensitivities of this quantity with respect to all independent variables.

1.1. Adjoint model generation via automatic differentiation

In a formal sense, the tangent linear model (TLM) of a given non linear model maps perturbations of independent variables such as the initial state to perturbations in the final state and the resulting objective function. For discretized problems the adjoint model ADM is the transpose of the tangent linear model, and the adjoint variables are equivalent to the Lagrange multipliers of the model. Physicists would refer to the adjoint method as the Lagrange multiplier method. For very complex non linear parent models such as an ocean general circulation model (GCM), which consists of the order of 10^5 lines of code, the task of developing an adjoint model, which faithfully represents the derivative of that model with respect to a high-dimensional control vector, is as challenging as the development of the parent model itself. Furthermore, the structure of the adjoint model depends on the control variables chosen, i.e., extending the control space may require extending the adjoint model (a drastic example is the use of bottom topography as the control variable in ocean modelling, e.g., Losch and Heimbach, 2007). Finally, if the parent model undergoes continued improvements, changes in algorithms, and extensions to incorporate new processes, a simultaneous update in the adjoint code is almost doomed to fail, unless equal resources for it would be available.

The route chosen by the MITgcm model developers was to systematically explore automatic or algorithmic differentiation (AD) (Griewank, 2000). AD is concerned with the accurate and efficient evaluation of derivatives for functions defined by computer programs. Source-to-source AD tools are capable of automatically generating code representing, for example, the tangent linear model, adjoint model, the Hessian, or other higher order derivatives of the non linear parent model code. The following steps are at the heart of the idea of AD:

1 consider a model as mapping from the space of independent variables controls to the space, often one-dimensional, of dependent variables (cost, objective/probing function, measure, diagnostic, ...).
2 this mapping is a composition of a large number of elementary operations; at an intermediate level one thinks of one time-step of a time-evolving problem, but ultimately each line of code represents such an elementary operation,
3 at the elementary level, the AD tool knows the derivative expression to each intrinsic function such as arithmetic and logical/conditional instructions,
4 the derivative of a composition of mappings can be rigorously computed via the chain rule; the result of the full derivative is the product of elementary Jacobians,
5 the full adjoint operator is the reverse-order product of the transposed elementary Jacobians.

For time-dependent problems the effect of transposing the TLM to obtain the ADM is to propagate information backwards in time (one could phrase it in terms of the TLM propagating perturbations, and the ADM accumulating sensitivities). The reverse nature of the integration, for transient problems, requires knowledge of the model state in reverse order. This is at the heart of the technical difficulties to generate efficient adjoint code for large-scale transient applications.

The AD tool chosen for MITgcm was TAMC and its commercial successor TAF developed by Giering and Kaminski (1998). It solves the problem of requiring model state variables in reverse temporal order through a hierarchical "check pointing" and targeted "taping" algorithm which provides an optimal mix between saving and recomputing required variables. To achieve this, the user has to guide TAF by the insertion of directives into the parent model to trigger storing of specific variables. This approach has rendered exact adjoint computation, i.e.,

#	configuration	resolution	time	# proc's	HPC platforms	comments
I	quasi-global	4 deg.	10^1 - 10^3 yr	1 to 2	PC	coupled ocean/biochem.
II	quasi-global	1 deg.	15 yr	48 - 96	Alktix, IBM DP, NEC SX-6	ECCO production
III	fully-global LLC	1/4 to 1 deg.	15 yr	72 to 324	Altix, IBM SP 4,5	next-generation ECCO
IV	Arctic Ocean	34 km	4 yr	40 to 80	Altix, IBM SP 4,5	coupled ocean/sea-ice
V	Southern Ocean	1/6 deg.	2 yr	600	IBM SP4 and BlueGene/L	eddy-permitting
VI	Tropical Pacific	1/6 deg.	1 yr	96	PC Beowulf cluster	eddy-permitting
VII	Labrador Sea	20 km	1 yr	8	AMD Opteron	couple ocean/sea-ice
VIII	Irminger Sea	4 to 9 km	15 - 30 days	1 to 32	AMD Opteron, Altix	eddy-resolving

Table 1: Some current adjoint applications on HPC platforms

Feature	Adjoint Support
NUMERICAL SCHEMES AND FEATURES	
parallel setup	full
parallel cubed-sphere topology	partly
partial cell topography	full
higher-order advection schemes	some (e.g. 3rd order DST)
multi-dimensional advection	full
staggered time-stepping	full
vector-invariant momentum	full
Bryan & Lewis (1979) mixing	full
bottom drag	fuyll (linear and quadratic)
nonlinear EOS	some (e.g. JMD95)
nonlinear free surface	partly
PACKAGES	
GM/Redi	partly (tapering-dependent)
bulk formulae	full (Large & Yeager, 2004)
sea-ice	mostly
BloECCO	mostly
open boundaries	mostly (except Orlanski)
passive tracers	full

Table 2: Major supported model features.

evaluating derivatives in reverse order, exact with respect to their time-varying model trajectory, practical for large-scale time-dependent applications.

Another critical point of concern is efficient implementation on various high performing computing (HPC) platforms. AD as applied to the MITgcm ensures that the adjoint model adopts the same parallel implementation strategy as the forward model. The adjoint model inherits the forward models' domain decomposition. Primitives of the parallel support package of the MITgcm have been adjointed by hand to overcome current limitations of AD tools to handle Message Parsing Interface (MPI) functions. The success of this approach is demonstrated by the number of adjoint applications that have been run on various HPC platforms, as listed in Table 1. Technical details related to hierarchical check pointing, adjoint dump and restart so-called divided adjoint or DIVA, adjoint parallelism, and active and adjoint variable I/O in the context of MITgcm are provided in Heimbach et al. (2002, 2005).

1.2. An up-to-date adjoint modelling infrastructure

The MITgcm model repository is transparently managed on-line via the Concurrent Version System (CVS). Through it the source code is changed on a daily basis. Currently, a total of 8 adjoint configurations, which employ various numerical schemes, features, and packages are tested every night to check whether developments to the forward model retain differentiability of the code with respect to the AD tool and preserve the computed gradient. For these configurations, the adjoint code is automatically generated every night based on the latest available forward code, and gradients are checked for 13-digit compatibility with respect to reference gradients. This ensures that up-to-date adjoint code can be maintained for the MITgcm. Most (but not all) features of the MITgcm can be made part of the adjoint. A summary of the most important features is listed in Table 2. Control variables currently supported by MITgcm are listed in Table 3.

2. Applications

The first sensitivity study using the MITgcm adjoint was conducted by Marotzke et al. (1999) to investigate effects on Atlantic meridional heat transport over a one-year period. The availability of three-dimensional Lagrange multipliers of the model state enabled the distinction between dynamical and kinematical effects of initial temperature anomalies, and demonstrated the power of the method to separate various processes affecting the heat transport.

The main driver, however, of the MITgcm adjoint model development was the Pacific acoustic tomography program (ATOC Consortium, 1998), the World Ocean Circulation Experiment (WOCE), and the satellite altimetric data, which were for the first time becoming available globally and continuously with the launch of TOPEX/POSEIDON in 1992 (Stammer et al., 1997). Combining these data with complementary observations from other satellite missions (e.g., SST and wind stress) and in-situ data collected during the WOCE period was thought to best be achieved through ocean state estimation (OSE) using an ocean model as dynamical interpolator e.g., Wunsch (2006).

2.1 Ocean state estimation

The term "state estimation" is borrowed from control theory, and as envisioned here, is directed (at the present time) not at forecasting, but at description and understanding. In control terminology, it addresses the smoothing problem rather than the filtering and prediction ones. As such, and in contrast to "data assimilation" for Numerical Weather Prediction (NWP), a premium is placed on avoiding trajectory jumps which occur at the analysis times in NWP and having control over the integrated space/time behaviour of many climatologically important properties e.g., heat content. Producing such a dynamically consistent description of the ocean was one of the primary goals of the JPL-MIT-SIO consortium called ECCO Estimating the Circulation and Climate of the Ocean founded in 1998 with D. Stammer as PI. The successful demonstration of OSE using the adjoint method came with the release and analysis of the first adjoint method-based quasi-global product by Stammer et al. (2002, 2003).

Since then, various improvements have been made (e.g., Heimbach et al., 2006), such as increasing horizontal resolution, extending the estimation period to 15 years covering 1992 to 2006 in the case of ECCO-GODAE (Wunsch et al., 2007) and to 50 years covering 1952 to 2001 in the case of GECCO (Köhl et al., 2006), update of existing and inclusion of various new data sources, improvement of various prior error estimates, notably for representation errors in conjunction with in-situ data (Forget and Wunsch, 2007), inclusion of an atmospheric boundary layer scheme, and update of numerical algorithms. See Wunsch and Heimbach (2007) for details.

Within ECCO, complementary estimation approaches are pursued at JPL, one led by I. Fukumori, using a Kalman filter and RTS smoother method (Fukumori 2002), one led by D. Menemenlis using a Green's function approach (Menemenlis et al., 2005b). Both efforts deserve their own description.

The data-constrained solutions are now being used to address important science questions surrounding decadal climate variability. Wunsch and Heimbach (2006) and Köhl et al. (2007) have placed lower bounds on month-to-month meridional heat and volume transport fluctuations in the North Atlantic, and noted the strong noise which masks weak, but non-significant decadal transport trends, and raises serious sampling and aliasing issues in hydrographic transport estimates. Vinogradov et al. (2007) analyze the seasonal cycle in global sea-level variations, while Wunsch et al. (2007) examine steric and

Control variables
• initial conditions (T,S,U,V • time-varying air-sea fluxes (buoyancy and momentum) • time-varying atmospheric state (surface air temperature, specific humidity, airpressure, downwelling shortwave radiation, wind speed vector) • surface relaxation timescales • time-varying prescribed open boundaries • mixing coefficients • bottom drag • bottom topography (requires special set-up) • passive tracer initial concentrations and fluxes • eddy stresses • sea-ice initial conditions

Table 3: Supported control variables.

mass contributions to decadal sea level trends, as well as their vertical partition between the upper and abyssal ocean, which is available from the full three-dimensional state estimate. Given the strong regional signals, they showed that both observation and calculation of global mean sea-level variations remain fragile.

The benefit of using a mean dynamic topography (MDT) to constrain the ECCO state estimates which is based on the geoid from the recent Gravity Recovery And Climate Experiment (GRACE) satellite mission has been demonstrated by Vossepoel (2007) and Stammer et al. (2007). The former provided an uncertainty assessment of available MDTs ahead of the European Gravity Field and Steady-State Ocean Circulation Explorer (GOCE) mission. Attempts are now under way (Ponte et al., 2007) to also use time-varying GRACE data in the form of monthly ocean bottom pressure. More application examples of the state estimates may be found in Heimbach and Wunsch (2007).

On a regional scale, the feasibility of higher-resolution state estimation in a nested context has been explored in several studies. Most have employed boundary conditions from a global solution as a starting point, and then improved the regional solution through adjusting the open boundaries as part of the control space. Examples for the Atlantic include the study by Ayoub (2006), by Gebbie et al. (2006) to study eddy subduction in the Eastern subtropics, and by Lea et al. (2006) in an eddy-resolving Irminger Sea context (Table 1, VIII). An eddy-permitting regional study in the tropical Pacific has been conducted by Hoteit et al. (2005) (Table 1, VI). In what is arguably the largest adjoint-based estimation effort undertaken so far, Mazloff (2007) has computed a preliminary solution of a two-year (2005/06) eddy-permitting (1/6 deg.) Southern Ocean state estimate (SOSE). This work involves a 600-processor adjoint model (Table 1,V). It contributes directly to NASA's Modelling and Analysis Project (MAP) "ECCO2 – High-Resolution Global-Ocean and Sea-Ice Data Synthesis" by J. Marshall at MIT and L.L. Fu at JPL/Caltech. By way of example, Figure. 1 page 20 depicts a snapshot of near-surface velocity taken on May 12, 2006 for iteration 16 of SOSE. Overlaid as a white line is the sea ice extent. The eddy-permitting character of SOSE is evident.

2.2 Sensitivity analysis

Application of the MITgcm adjoint for sensitivity analyses has moved in various directions, and following the AD route has also enabled us to keep pace with various coupling efforts within the MITgcm modelling framework.

Köhl (2005) extended the work of Marotzke et al. (1999) to a 10-year study of North Atlantic MOC sensitivities. They show which geographical locations are optimally suited for measuring MOC changes, and assess dominant mechanisms influencing the MOC on various time scales from annual to decadal. Going far beyond these time scales, Bugnion et al. (2006a,b) considered multi-centennial equilibrium sensitivities of the MOC. The sensitivity maps enable quantification of the relative role played by buoyancy vs. momentum forcing, and by diapycnal mixing. Furthermore, different surface boundary conditions resulted in fundamental differences in the sensitivity patterns, providing a clear confirmation of the importance of the type of boundary conditions used for climate-time scale integrations.

Focusing on the tropical Pacific, Lee et al. (2000) and Fukumori et al. (2004) investigate the subtropical-tropical water mass exchange and its impact on the Niño-3 region via adjoint advection and diffusion of passive tracer-tagged water masses.

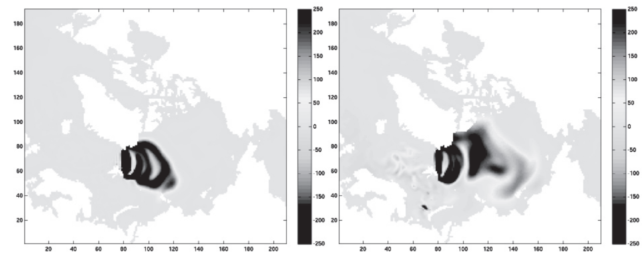

Figure 2: Adjoint sensitivity of sea-ice export through Fram Strait to ice thickness distribution everywhere in the Arctic and sub-Arctic domain over a 4-year period between 1992 and 1995. The coupled ocean/sea-ice adjoint model runs on 80 processors and was generated using TAF.

In a similar context, Galanti and Tziperman (2003) study mid latitude ENSO–teleconnection mechanisms using the TAMC-generated adjoint of an early alpha version of MOM4. They find strong sensitivities to planetary Rossby waves, which are amplified in baroclinically unstable regions of the subtropical gyre, and may account for decadal ENSO variability.

Dutkiewicz et al. (2006) developed an adjoint component of their biogeochemical model which is coupled to the offline adjoint MITgcm dynamical core. The coupled adjoint was used to investigate controls and limitations to global biological productivity and air-sea carbon fluxes. In particular, regional patterns of iron vs. light sensitivities highlighted the interplay of phosphorus, iron and light limitation. Extension of the coupled ocean/biogeochemical adjoint to enable coupled ocean carbon cycle studies is anticipated.

In the light of concerns regarding the evolution of the Arctic sea-ice cover that have received significant attention in the ongoing International Polar Year (IPY), we have increased our effort at completing an adjoint component of MITgcm's fully-fledged dynamic/thermodynamic sea-ice model (Heimbach and Menemenlis, 2003, Losch et al., 2008). The coupled ocean/sea-ice adjoint is now being used in a regional Arctic configuration, which is a slightly coarsened (roughly 30 km horizontal resolution) version of the ECCO2 cubed-sphere setup of Menemenlis et al. (2005a). Figure. 2 depicts transient sensitivities of sea-ice export through the Fram Strait to changes in ice thickness everywhere in the Arctic and sub-Arctic domain over a 4-year period between 1992 and 1995. The dominant pattern is a positive signal (an increase in ice thickness by a unit perturbation at position (x, y) will increase sea ice export by a magnitude shown in the map) expanding away from the Fram Strait into the Arctic interior, in agreement with the time-reversed circulation in the Arctic. Time scales of sea-ice advection connecting the Fram Strait to various areas of the Arctic domain become clearly visible.

3. OpenAD: a new AD tool

Given the importance of the AD tool for ECCO and for various MITgcm applications, we are involved, together with Argonne National Lab, in the development of a new open-source tool, called OpenAD (Naumann et al., 2006, Utke et al., 2008) as a backup and complement to the current tools in use. The project has been supported by NSF's Ocean Science Division and by NASA's MAP project ECCO2. It represents the largest AD tool development effort currently under way within the computational mathematics and AD community. The tool has now been successfully applied to the full MITgcm in a configuration very similar to the one of Bugnion et al. (2006a), i.e. a coarse-resolution setup, including partial cell topography, convective adjustment, and a GM/Redi parameterization scheme, all of which are part of the adjoint. To underline the value of the availability of complementary AD tools we report here two instances in which adjoint gradients between the two tools were compared for equivalent setups. In one case the comparison helped to isolate a bug in the TAF tool, in the other case, a bug in OpenAD was found. The MITgcm gradients computed by the tools typically agree to within at least 7 digits. Performance-wise, for the same checkpointing hierarchy (level-3 checkpointing), the ratio between a full adjoint and a forward integration is on the order of 5 using the TAF-generated adjoint, and 10 using the OpenAD-generated code. The origin of these differences are the different approaches of optimizing storing vs. recomputation requirements (store-all vs. recompute-all approaches). Numbers given above are expected to change in the future.

The OpenAD-generated adjoint has been applied to compute sensitivities globally of North Atlantic heat transport over a 100 year period, similar to the work of Bugnion et al. (2006a), but focusing here on the transient aspect. Figure 3 (page 20) shows sensitivities of meridional heat transport across 26 N in the Atlantic to changes in temperature at 1250 m depth, 2 (panel a) and 75 (panel b) years prior in the past. Sensitivities are mediated through a complex interplay of various processes which act on different time scales, ranging from coastal Kelvin waves, Rossby waves (here visible snapshots of adjoint waves) and advective processes (again in time-reversed, adjoint fashion). For instance, while Figure. 3a reflects comparatively local influences on heat transport changes limited by maximum wave propagation speed, Figure. 3b shows that on multi-decadal time scales, the problem of Atlantic heat transport variability becomes a global problem, as one might expect.

Many challenges lie ahead. A partial list includes expanding the work on the interpretation of adjoint sensitivities duals, extending adjoint calculations to complex coupled models, further exploring the limit of high-resolution state estimation with the adjoint method, and using other mathematical tools which require derivative code such as tangent linear, adjoint and Hessian models to address problems of climate science. A variety of tools and adjointable models will undoubtedly be beneficial to improve confidence in this type of modelling.

Acknowledgement:
This work is supported by the National Ocean Partnership Program NOPP with contributions from NASA, NSF and NOAA, and additional NASA funding. The ongoing development is a team effort of the MITgcm and ECCO groups, involving A. Adcroft, J.M. Campin, S. Dutkiewicz, C. Evangelinos, I. Fenty, D. Ferreira, G. Forget, R. Giering, C. Hill, E. Hill, A. Köhl, M. Losch, M. Mazloff, D. Menemenlis, A. Nguyen, R. Ponte, D. Stammer and J. Utke, and supported over the years by J. Marshall and C. Wunsch. Thanks are due to our various ECCO partners who contributed to aspects of this work. Computer resources at GFDL, SDSC, NASA/ARC and NCAR are acknowledged.

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AOMIP: coordinated activities to improve models and model predictions

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AOMIP motivation

A note published by Sasowsky (2006) in Eos is one of the important motivations for the organization of "Model Intercomparison Projects" and, in particular, the Arctic Ocean Model Intercomparison Project (AOMIP): "Of 29 numerical modeling studies reviewed by Bredehoeft (2005), between seven and ten included 'surprises' where natural phenomena and model predictions of those phenomena diverged. Konikow et al. (1997) found that six different groups of modeling experts all made fundamental errors in implementing the same numerical boundary condition for a model test case. Oreskes and Belitz (2001) identified three factors—non-uniqueness, temporal and spatial divergence, and subjectivity of model assessment—inherent in contemporary numerical model predictions of natural systems that they argue make such predictions unreliable. These cautions should be taken seriously." Interestingly, the initial AOMIP studies have revealed striking differences among Arctic model results. The question was and still is: What are the causes of these differences: errors of model implementation, forcing, boundary conditions, model physics, numerics, or design of numerical experiments? Some of these questions or probably all of them are relevant to the results of global climate models represented in IPCC studies. In order to address these questions for the Arctic Ocean environment, the AOMIP was organized in 2001. It has created a broad-based energetic and motivated "community" of directly involved Arctic modelers from the U.S.A., Canada, Germany, United Kingdom and Russia (http://efdl.cims.nyu.edu/project_aomip).

AOMIP foci and approach:

AOMIP has been focused on Arctic regional coupled ice-ocean model intercomparisons and investigations of different aspects of ocean and sea ice changes for the time period 1948-present. Among the major themes were investigations of the origin and variability of Atlantic Water (AW) circulation (e.g. Gerdes et al., 2003; Karcher et al., 2002, 2003, 2007; Golubeva and Platov, 2007; Zhang and Steele, 2007), mechanisms of accumulation and release of fresh water (e.g. Steele and Flato, 2000; Proshutinsky et al., 2002; Häkkinen and Proshutinsky, 2004; Steiner et al., 2004; Uotilla et al., 2005; Proshutinsky et al., 2005; Dukhovskoy et al., 2004, 2006a, 2006b), causes of sea level rise (e.g. Proshutinsky et al., 2002, 2004, 2007b), and the role of tides in the shaping of climate (e.g. Hibler et al., 2006, Holloway and Proshutinsky, 2007). In the course of these investigations, problems with numerical implementation, and validation against observations have been emphasized. Some problems have been found to occur only in a few models, while others have been found in many or most. Exposing these issues is an extremely important part of AOMIP, and would have been difficult or impossible to achieve without coordinated activities. Preliminary investigations into improving the models have also been initiated by AOMIP. AOMIP is not a "top-down" organization that can dictate model changes to all participants. Rather, a vital function of this project is to expose consistent problems in numerical models and then to provide a forum for individual investigators to propose solutions.

The AOMIP approach is to leverage the existing financial support of each participant for a comparative analysis of different models and scientific results. This strategy has provided a unique opportunity to coordinate AOMIP studies via a set of carefully-planned numerical experiments covering the most important processes and interactions. A clear advantage was that each AOMIP participant was able to work with her/his specific research theme using simulation results from all AOMIP models and to analyze differences and test hypotheses using a multi-model suite of outputs. The result is a synthesis that integrates observational and modeling efforts toward the overall goal of developing advanced Arctic models able to accurately reconstruct past, describe current and predict future Arctic conditions. We view AOMIP as a collaborative frame-work wherein modelers and observers discuss results, problems, and new ideas, all with the goals of model improvement and better understanding of the Arctic climate system.

AOMIP models and results

During 2001-2007, the AOMIP group has consisted of a core of nine principal investigators, and a large number of co-investigators from different countries (see AOMIP web site). Model parameters including domains, vertical and horizontal resolutions, initial and boundary conditions are described in Holloway et al. (2007) and at the web site http://www.planetwater.ca/research/AOMIP/modelspecs.html. In AOMIP, z-coordinate models dominate that are mostly based on the same original code (Bryan, 1969) but are, nonetheless, sufficiently distinct in their detailed treatment of physical processes as to warrant intercomparison. As an example, the Institute of Ocean Sciences (IOS, Canada) model replaces the traditional Newtonian formulation of viscous damping with an eddy-topography rectification, a parameterization known as the Neptune effect. A variant of the most-widely used isopycnic model (Bleck and Boudra, 1981) is represented in AOMIP by the New York University (NYU) model. AOMIP also employs several versions of a sigma-coordinate model (Blumberg and Mellor, 1987) represented, for example by the Goddard Space Flight Center (GSFC, USA) and International Arctic Research Center (IARC, USA) models. The basic configuration for all participating models is to have their ocean model coupled to a sea-ice model and to be driven by specified atmospheric forcing fields.

The sea ice models differ in both dynamics (viscous plastic, general viscous or elastic-viscous-plastic or cavitating fluid dynamics) and in thermodynamics (heat and salt fluxes, number of sea ice categories, layers and snow parameters). Holloway et al. (2007) provides detailed characteristics for each of 14 AOMIP models.

Three publications (Proshutinsky et al, 2001a, 2005; Proshutinsky and Kowalik, 2007a) have outlined the major AOMIP results for the broad community. The special JGR section "Arctic Ocean Model Intercomparison Project Studies and Results" was published in 2007 (JGR, vol. 12, No C4, 2007), summarizing results of past AOMIP activities (hereafter AOMIP-2007). Since 2001, AOMIP has organized 11 workshops, published more than 50 peer-reviewed papers and resulted in more than 80 presentations. AOMIP workshops took place at different locations (Naval Postgraduate School, University of Washington, Woods Hole Oceanographic Institution, Geophysical Fluid Dynamics Laboratory, McGill University, and University of Hawaii) in order to involve students from these institutions in Arctic studies.

One unresolved question for climate studies is: How to force regional models at lateral and surface boundaries based on AOMIP experience? This problem has not received much attention in AOMIP, since most model southern boundaries lie far south from the Arctic Ocean and thus their role in the Arctic's simulated climate variability may be minimal (e.g. Proshutinsky et al., 2002 Dukhovskoy et al., 2004, 2006). For example, the GSFC and ICMMG models include the entire North Atlantic and the other models southern boundary (except the global CNF, LANL and POL models; see Holloway et al., 2007) is located at 50N or at least includes the Greenland, Iceland and Norwegian Seas (GIN Sea). The NPS model has all boundaries closed and no water mass flux is allowed through the lateral boundaries, but a 30-day restoring to monthly temperature and salinity climatology is used there. Other models assign water temperature and salinity on inflow based on climatology and prescribe "free" T and S outflow (i.e. mapped from the interior grid point,as in the IOS model). At the southern boundary (15° S) of the GSFC model the salinities and temperatures are relaxed to Levitus et al., (1994a, 1994b) climatology (hereafter Levitus climatology) values in five grid rows from the boundary. Immediate restoring of temperature and salinity is used at the Mediterranean outflow point. The AWI model's southern model boundary approximately runs along 50°N and the open boundary condition was implemented following Stevens (1991). This boundary condition allows the outflow of tracers and the radiation of waves. At inflow points determined by the model, temperature and salinity are specified according to Levitus climatology. The baroclinic part of the horizontal velocity is calculated from a simplified momentum balance while the barotropic velocities normal to the boundary are specified from a lower resolution version of the model that covers the entire North Atlantic. Other boundaries are treated as closed walls. From the several examples described above, one sees that a) AOMIP has "tested" at least three different approaches (open boundaries, closed "wall" boundaries, and global models), and b) none of the AOMIP models have reported any substantial

continued on page 23

From Fox Kemper et al, page 2: Parameterising Submesoscale Physics in Global Climate Models.

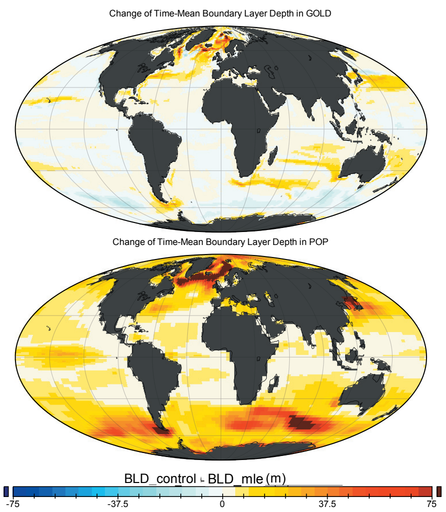
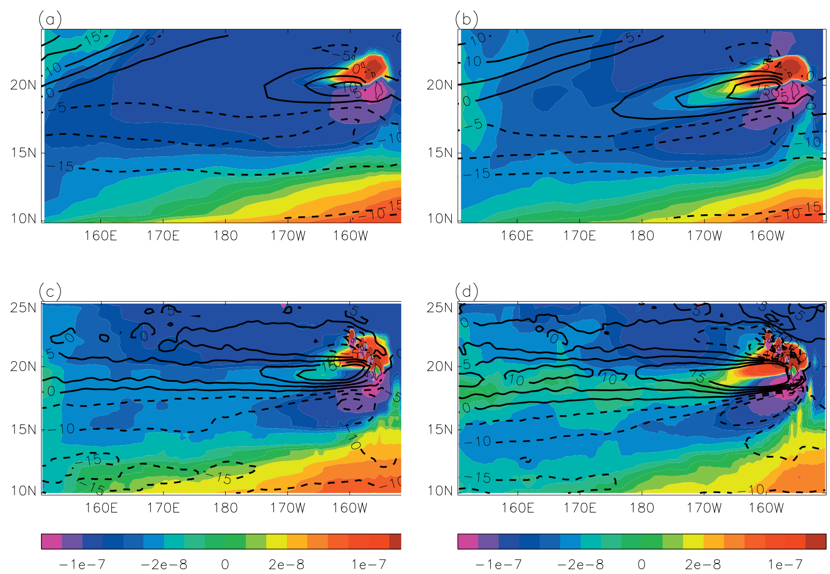


Fig. 1: Reduction in boundary layer thickness with the introduction of the MLE parameterization in GOLD (upper) and POP (lower). The average over the last ten years of the simulations are shown. The boundary layer is the layer over which finescale mixing due to winds and convection is active. Generally, it is less than or equal to mixed layer depth.

From Roberts et al (page 8): Impact of relative atmosphere-ocean resolution on coupled climate models

Figure 3: Wind stress curl (colour, Nm^{-2}/m) and ocean zonal current at 35m (contours at 5cms^{-1} intervals, eastward currents solid, westward currents dashed). (a) lowest resolution (HadGEM), (b) higher resolution atmosphere, (c) higher resolution ocean, and (d) high resolution atmosphere and ocean (HiGEM).



From Nakano et al, page 11: Development of a global ocean model with the resolution of 1° x ½° and 1/8° x 1/12°

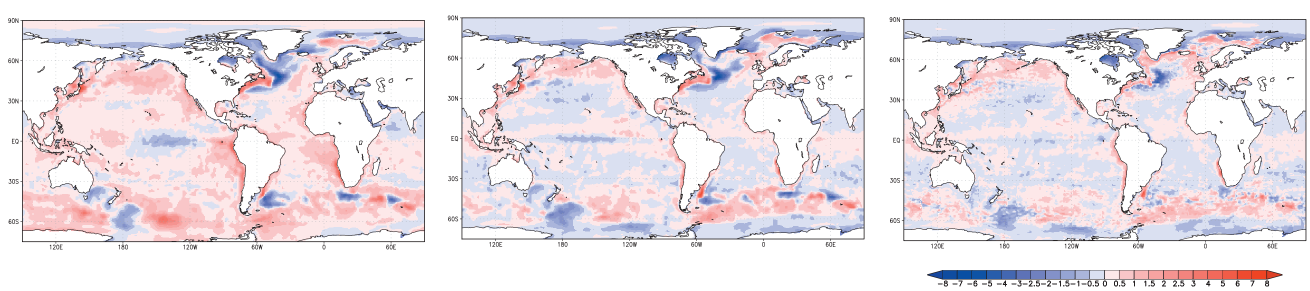


Figure 1: Bias of annual mean sea surface temperature in °C of the last two years of the runs. (a) Coarse-CORE run (b) Coarse-JRA run (c) Fine-JRA run.

From Nakano et al, page 11: Development of a global ocean model with the resolution of 1° x ½° and 1/8° x 1/12

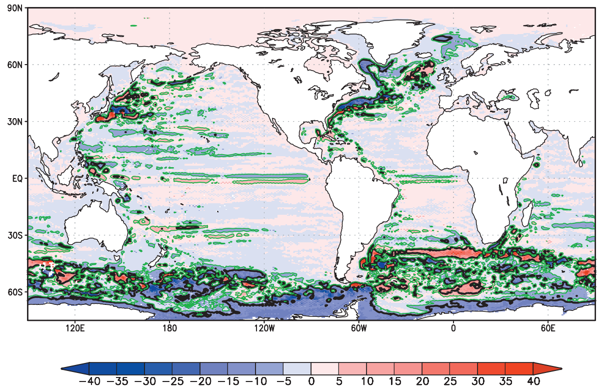


Figure 2: Difference in barotropic stream functions in SV of the last two years between Fine-JRA and Coarse-JRA run (Fine-JRA minus Coarse-JRA). Green lines indicate ±5SV and black lines indicate ±10 SV.

From Heimbach et al., page 13:The MITgcm/ECCO adjoint modelling infrastructure

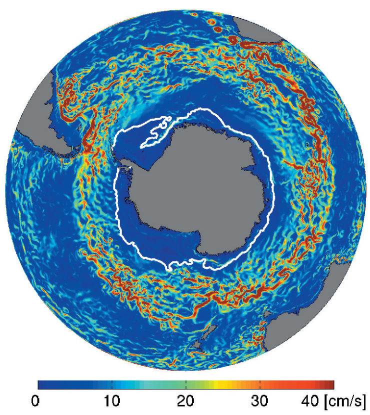


Figure 1: Snapshot of near-surface speed on May 12, 2006 for iteration 16 of the ECCO Southern Ocean State Estimate (SOSE). The underlying setup is the MITgcm and its adjoint at 1/6o horizontal resolution. Overlaid as white line is the sea ice extent as computed with the dynamic/thermodynamic sea ice model. Courtesy M. Mazloff [2007].

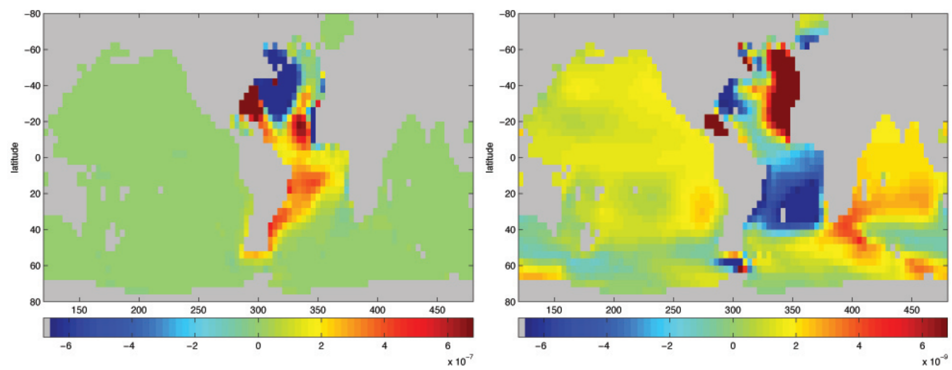


Figure 3: Sensitivities of meridional heat transport across 26N in the Atlantic to changes in temperature at 1250 m depth 2 (a) and 75 (b) years prior in the past. The calculation was based on the OpenAD generated adjoint of the MITgcm at 4o horizontal resolution. Note the different scales between the panels.

From Proshutinsky et al, page 17: AOMIP: coordinated activities to improve models and model predictions

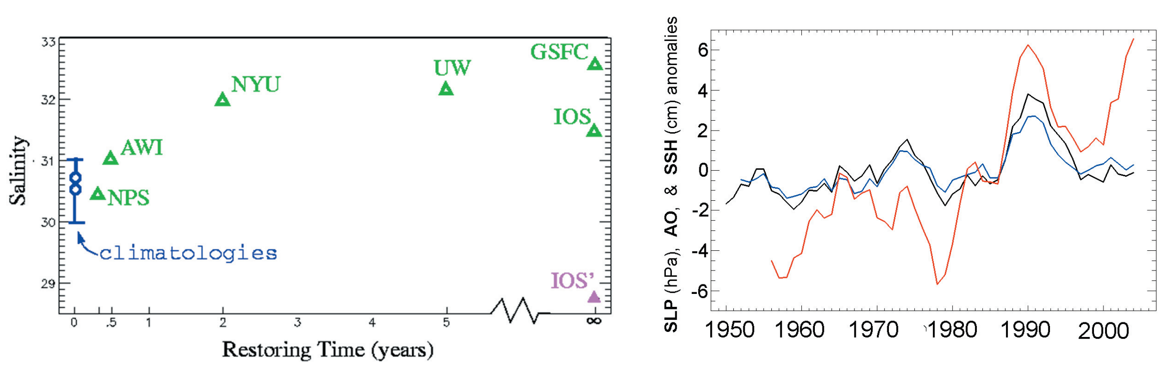


Fig. 1 Left: Mean April sea surface salinity (triangles) within the Beaufort Gyre, in comparison with mean (open circles) and max/min (horizontal bars) climatological values. As the unrealistic climate restoring term is weakened (longer restoring time constant) the modeled salinity drifts towards an unrealistically salty asymptotic value of about 33 (Steele et al., 2001). Note that GSFC and IOS models have no restoring corrections because their restoring time is infinite. Right: Annual anomalies of sea level at 9 tide gauge stations located along the Siberian coastline (red). The blue line is the 5-year running mean anomalies of the annual mean Arctic Oscillation (AO) index multiplied by 3. The black line is the SLP anomaly at the North Pole (NCAR/NCEP reanalysis) multiplied by -1. The correlation between sea level and AO before 1996 is higher than 0.8. After 1996 the AO is low and stable but sea level continues rising.

From Agarwal et al, page 28: Impact of different Bulk Parameterization schemes of air-sea fluxes on Oceanic heat content in the Tropical Indian Ocean

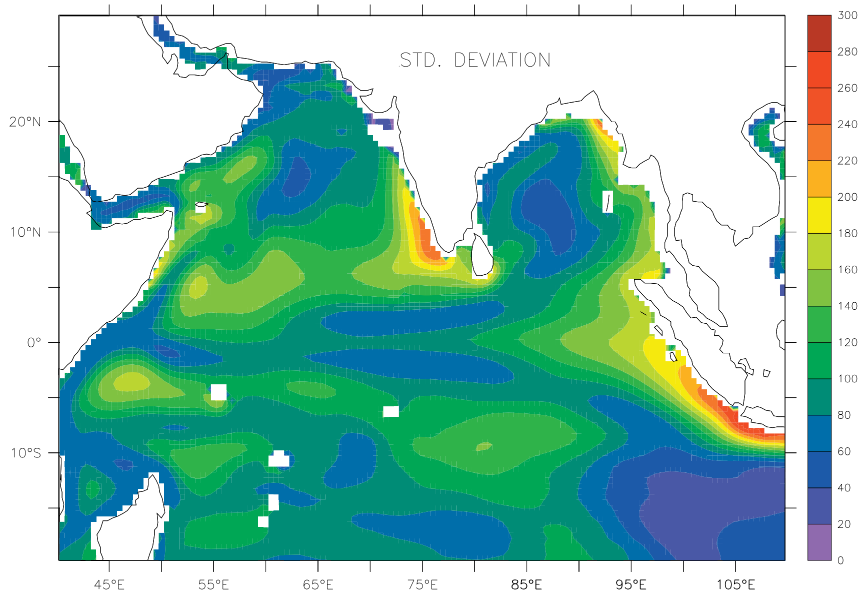


Figure 1. Standard Deviation of model(E2) simulated Heat Content during 2003-2004.

From Legler et al, page 33: US CLIVAR Drought Predictability Research Focus

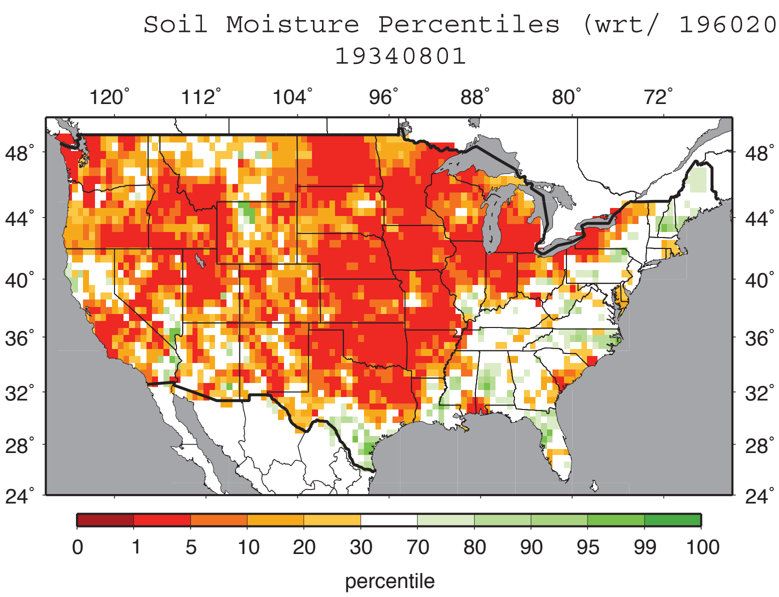


Figure 1. Spatial extent of the Dust Bowl drought of the 1930s in August 1934. Percentiles are for soil moisture relative to the 85-year period 1915-2003. From University of Washington Surface Water Monitor, available online at: http://www.hydro.washington.edu/forecast/monitor

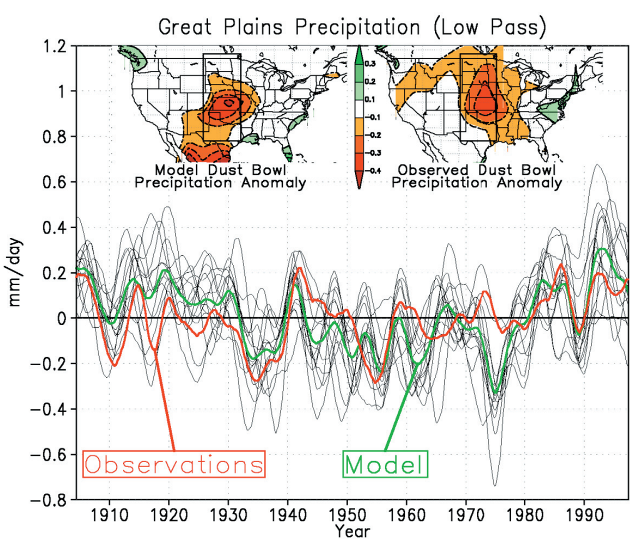


Figure 2. Time series of precipitation anomalies averaged over the U.S. Great Plains region (30°N to 50°N, 95°W to 105°W), from Schubert et al. (2004). A filter has been applied to remove time scales shorter than about 6 years. The thin black curves are the results from 14 ensemble members from C20C global model runs. The green solid curve is the ensemble mean. The red curve is based on observations. The maps show the simulated (left) and observed (right) precipitation anomalies averaged over the Dust Bowl period (1932 to 1938, units mm/day).

From Balmaseda et al., page 36: The Ocean Component at ECMWF: Towards a seamless prediction system

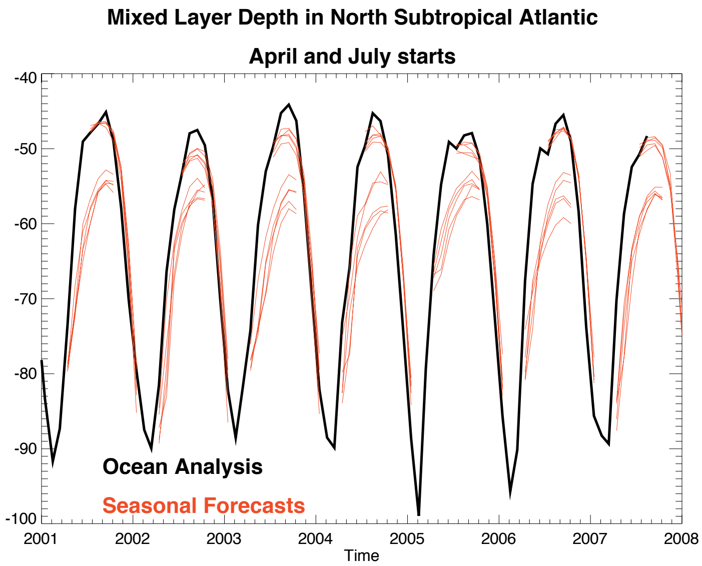
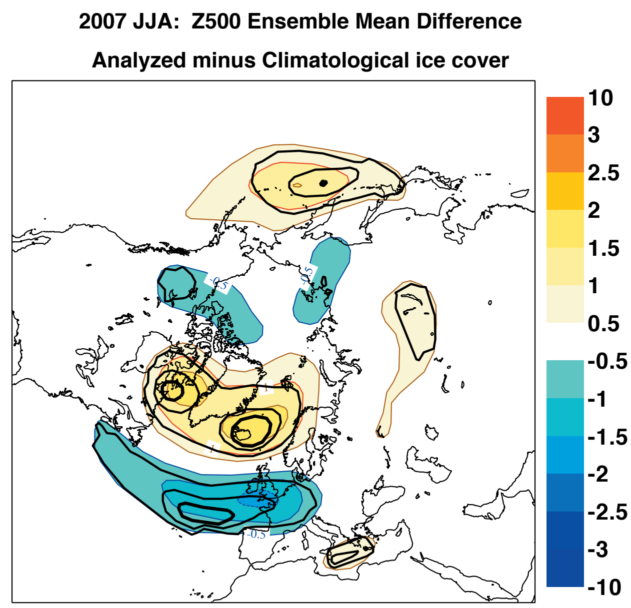


Figure 1. Time series of the mixed layer depth in the North Subtropical Atlantic (5N-28N), from the ocean analysis (black) and from seasonal forecasts initialized in April and June. The forecasts initialize in April systematically overestimate the depth of the mixed layer.

Figure 2: Impact of the summer 2007 ice anomaly on June-July-August Z500, as measured by the ensemble mean difference between two experiments in which the atmosphere model is forced by the 2007 analyzed ice coverage and by climatological ice respectively. The experiments, with 20 ensemble members each, were initialized in May 2007 and run for the 5 months forced by observed SST. Units are dam. The 80%, 90% and 95% significance level are shown by the black contours.



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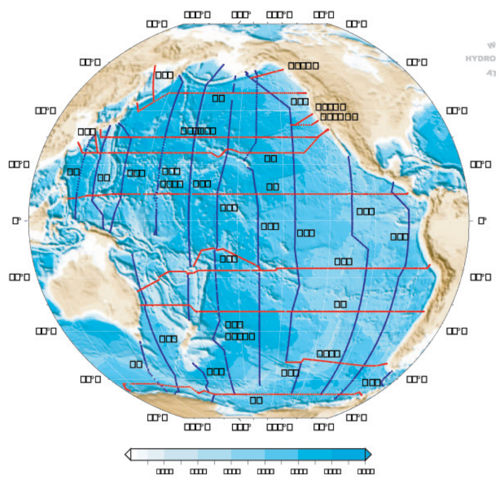

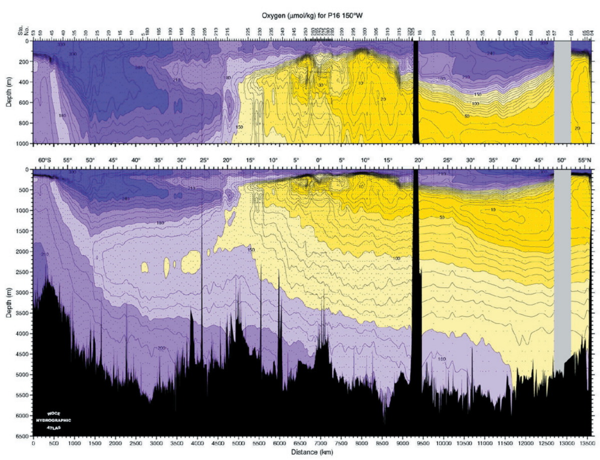

Left Pacific station positions Right Dissolved oxygen Section P16

continued from page 18

problems with their results associated with open boundary conditions.

The surface heat and especially fresh water (FW) flux forcing problem in AOMIP studies has been contentious. Initially, AOMIP recommended avoiding restoring and flux correction procedures. Unfortunately, this was not followed by all AOMIPers, and even some who reluctantly gave up salinity restoring have since reverted. Among AOMIP models cited above only three models report a no restoring approach (IOS, UW, and GSFC). The GSFC model has some drift in ocean salinity but after filtering the salinity trend it demonstrates excellent results picking seasonal, interannual and decadal variability very well. All other modeling teams have voted for restoring procedures with different restoring time. Steele et al (2001) have shown (Figure 1, page 20) that surface salinity in the center of the Beaufort Gyre generally increases with increasing restoring time. However there are two points marked "IOS", the second of which, also with no restoring, has the lowest surface salinity which could be explained due to changes in wind forcing (more converging and respectively more fresh water in the center of the Beaufort Gyre). Other models may or may not have this same effect, depending on their restoring and mixing procedures. Zhang and Steele (2007) and Golubeva and Platov (2007) originally focusing on the problems of the Atlantic water circulation and trying to explain why their model generates anticyclonic motion of the Atlantic layer instead of cyclonic rotation practically independently have found that when they limited oceanic mixing below the surface mixed layer, they obtained better circulation patterns of the Atlantic layer and also were able to simulate better vertical water temperature and salinity profiles. They concluded that the upper ocean salinification observed in Figure 1 comes from deeper layers due to too much mixing. Zhang (personal communication) has also reported that their model does not need restoring after the mixing problem was fixed.

The role of surface freshwater flux boundary conditions in prognostic Arctic Ocean/sea-ice modeling was also analyzed by Prange and Gerdes (2006) using a regional numerical model. Three different applications of freshwater flux formulations were evaluated. The standard formulation, which serves as a benchmark, takes surface volume fluxes due to precipitation, evaporation and river runoff into account. The total freshwater input to the Arctic Ocean by runoff, precipitation and Bering Strait inflow is approximately 6800 km^3 yr^{-1} in the model setup. The implementation of an Arctic river water tracer in the standard run enables the calculation of an average mean residence time of 14–15 years for river water in the Arctic halocline. The second formulation for surface freshwater fluxes neglects the volume input, which corresponds to applying 'virtual salinity fluxes'. This simplification leads to a rapid salinity build-up in the upper layers of the Arctic Ocean and causes a substantial reduction of freshwater export through Fram Strait. The third formulation uses a constant reference salinity of 35 in the definition of the virtual salinity flux boundary condition. This approach results in hydrographic fields which are very similar to those from the standard run. Errors in circulation and freshwater transport are small and, for most applications, tolerable. Their results suggest that virtual salinity fluxes with fixed reference salinity are a reasonable approximation for Arctic Ocean models with horizontal resolution of order 100 km.

However, because of large uncertainties in high-latitude surface fresh water fluxes and inherent model shortcomings, a simulated equilibrium will in general not be realistic in terms of horizontal transports and regional storage of fresh water without further constraints. A technique that can be used in regional models has recently been applied by Köberle and Gerdes (2007). The model was started from initial conditions and integrated for several periods of the NCEP–NCAR reanalysis forcing using restoring of surface salinity. The model

Table 1 Project participants.

Institute, PI(s)	Country	Abbreviation
Arctic and Antarctic Research Institute, A. Makshtas	Russia	AARI
Alfred Wegener Institute, R. Gerdes and C. Koeberle	Germany	AWI
Dalhousie University, F. Dupont	Canada	DAL
Florida State University, E. Chassignet and D. Dukhovskoy	USA	FSU
Geophysical Fluid Dynamics Laboratory, S. Griffies, M. Winton	USA	GFDL
Goddard Space Flight Center, S. Hakkinen	USA	GSFC
International Arctic Research Center, B. Hibler, G. Panteleev	USA	IARC
Institute of Marine Sciences, UAF, M. Johnson	USA	IMS
Institute of Ocean Sciences, G. Holloway	Canada	IOS
Jet Propulsion Laboratory, R. Kwok, A. Nguyen	USA	JPL
Los Alamos National Laboratory, E. Hunke	USA	LANL
Massachusetts Institute of Technology, C. Hill	USA	MIT
Naval Postgraduate School, W. Maslowski	USA	NPS
National Center for Atmospheric Research, M. Holland	USA	NCAR
New York University, D. Holland	USA	NYU
Norwegian Polar Institute, Ole Anders Nøst	Norway	NPI
Ocean and Atmosphere Systems, M. Karcher and F. Kauker	Germany	OASYS
Proudman Oceanographic Laboratory, M. Maqueda	UK	POL
Russian Academy of Science, Moscow, N. Yakovlev	Russia	RASM
Russian Academy of Science, Novosibirsk, E. Golubeva	Russia	RASN
Swedish Meteorological and Hydrological Institute, M. Meir	Sweden	SMHI
University College London, S. Laxon	UK	UCL
University of Massachusetts, Dartmouth, C. Chen	USA	UMAS
University of Washington, M. Steele, J. Zhang	USA	UW
Woods Hole Oceanogr. Ins, A. Proshutinsky, P. Winsor, A. Condron	USA	WHOI

was then reinitialized with the result from the end of the third cycle of NCEP–NCAR forcing. For the repetition of the fourth forcing cycle, the restoring of surface salinities was switched off and replaced by the annual mean climatology of the restoring term applied as a fixed salt flux to the surface box of the ocean model. This procedure is not recommended for long-term integrations with global models as it represents one version of mixed boundary conditions that lead to unrealistic oscillations of the large scale ocean circulation.

Goals and planned activities

The first 5-year AOMIP research cycle was completed in March 2007 and AOMIP is seeking new funding to pursue its goals, taking into account new circumstances in Arctic change and science developments. It is important to continue these studies because the research and integration activities of AOMIP are now well established and progressing towards starting model improvement, testing and validation experiments in order to develop and verify a comprehensive Arctic regional model and improve global climate models for the Arctic region. Thus, the overall AOMIP science goals are:

- Validate and improve Arctic Ocean models in a coordinated fashion.
- Investigate the variability of the Arctic Ocean and sea ice at seasonal to decadal time scales, and identify mechanisms responsible for the observed changes.

The project's practical goals are to:

- Maintain and enhance the established AOMIP international collaboration to reduce uncertainties in model predictions;
- Support synthesis across the suite of Arctic models and organize scientific meetings and workshops;
- Conduct collaboration with other MIPs with a special focus on model improvements and analysis;
- Disseminate findings of AOMIP effort to broader communities;
- Train a new generation of ocean and sea-ice modelers.

Participants and methods

It is expected that 25 institutions (Table 1, page 23) will be involved in AOMIP studies in the next research cycle. Table 2 shows their interests and foci of research. Realistically we anticipate each group to perform the experiment(s) that most closely follow their already-funded interests but two coordinated experiments are proposed for all modeling groups. The first experiment will be a ~50-year simulation of the years 1948-present with (i) improved forcing (see Hunke and Holland, 2007 for details) and (ii) improved models (see recommendations in AOMIP-2007). Comparing new improved and control model runs with observations will allow AOMIP to: (i) estimate results of model improvements; (ii) validate models against observations and (iii) assess model uncertainties. In parallel, model results will be used for the investigation of Arctic climate variability. For example, for AOMIP purposes GFDL will employ the global atmosphere dataset developed at NCAR by Large and Yeager (2004). This dataset has been sanctioned by the CLIVAR Working Group for Ocean Model Development. This experiment will significantly increase the number of collaborating international scientists interested and able to participate in AOMIP activities.

The second experiment is guided by growing interest in the longer-term climate variability of the Arctic climate system, including e.g., the 1930s warm period. The experiment will be carried out for ~100-year period under forcing reconstructed by the Alfred Wegener Institute group (Kauker et al., submitted to JGR; see also AOMIP web site). Results from other participating models running this experiment will be used to reconstruct ice/ocean conditions for 1900-present and then to see how AOMIP models behave during long-term integrations.

AOMIP basic activities include model improvements, process and climate change studies. Details of some of them are described below and for each institution are shown in Table 2.

Table 2 AOMIP major activities

Group	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
Model improvement (numerics)			X		X		X		X	X	X		X			X		X	X	X					X
Model improvement (parameterization)	X		X		X	X	X		X	X	X		X	X	X	X		X	X	X	X	X		X	
Model improvement (forcing)	X					X	X	X				X		X									X		
Model improvement (restoring/flux correct.)		X				X						X			X		X								X
Model improvement (resolution)		X		X		X	X				X	X	X		X		X	X	X	X					
Model improvement (validation)	X		X	X	X	X	X		X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X
Process studies (fresh water)	X	X	X		X	X		X	X	X		X		X	X		X		X	X			X	X	
Process studies (Atlantic layer)	X	X		X	X					X		X		X	X		X	X	X	X	X		X	X	X
Process studies (Pacific water)	X		X						X	X		X			X		X			X	X		X	X	X
Process studies (Coastal currents)												X			X		X	X		X			X		
Process studies (Tides in ocean and ice)							X					X			X			X	X			X	X		
Process studies (Fast ice)	X							X								X			X			X			
Process studies (River runoff)																			X	X			X	X	X
Process studies (Open boundaries)				X		X													X				X		
Process studies (Deep/bot. water formation)																		X							X
Process studies (Halocline)										X														X	
Process studies (Eddy trans.: heat/salt/mom.)														X											X
Global – Arctic connections		X	X	X	X	X	X	X	X	X	X	X	X	X				X		X			X	X	X
Climate change	X	X			X	X		X		X	X	X	X		X		X	X		X	X	X	X	X	X
50-year coordinated improved model exp.	X	X	X	X	X	X	X	X	X			X			X	X	X		X	X	X		X	X	
100-year coordinated improved model exp.		X		X	X			X				X			X	X			X	X	X				
Data assimilation	X						X					X					X						X	X	X

01 – AARI; 02 – AWI; 03 – DAL; 04-FSU; 05 – GFDL; 06-GSFC; 07 – IARC; 08 – IMS; 09 – IOS; 10 – JPL; 11 – LANL; 12 – MIT; 13 – NCAR; 14 – NPI; 15 – NPS; 16 – NYU; 17 - OASYS; 18 – POL; 19 – RASM; 20 – RASN; 21 – SMHI; 22 – UCL; 23 – UMAS; 24 – UW; 25 – WHOI.

Intercomparison and model validation procedures include the implementation of common grids, coordinated interpolation techniques, a set of integrated parameters such as heat, freshwater content, potential vorticity, topostrophy (defined as fxV·S, where f is Coriolis vector, V is model velocity vector, and S is gradient of total depth, Holloway et al., 2007), ice area and extent, etc. These procedures will also include data mining and reconstruction methods (Panteleev et al., 2007).

Model Improvements

This activity addresses Goal #1: "Validate and improve Arctic Ocean models in a coordinated fashion," by focusing on three broad areas of model improvement. The first area includes the use of observations for model forcing (including initial and boundary conditions) and validation. Some of the recommended work associated with this was described in AOMIP-2007 and is related to data collections, gridding and validation for AOMIP purposes. The second area is model numerics and parameterization of different processes (e.g. mixing, advection). An example is the introduction of the eddy rectification effect over sloping topography (Holloway, 2004; Holloway et al., 2007), which is incorporated into several relatively coarse resolution models (DAL, IOS, POL and RASN; see Table 2) and has been shown to drive a "cyclonic rim current" around the Arctic basins. Numerical improvements include the introduction of second order moments based advection (e.g. Prather, 1986; Hofmann and Morales Maqueda, 2006; Morales Maqueda and Holloway, 2006; Holloway et al., 2007) and improved mixing (Zhang and Steele, 2007; Golubeva and Platov, 2007) in several AOMIP models. These activities will be continued in other models and also expanded to implement new methods/algorithms/physics. The third area of model improvement will be the inclusion of processes important for the Arctic such as tides and ice dynamics. Preliminary experiments have shown that tidal and inertial sea-ice motion leads to additional generation of sea-ice mass and can improve mixing and allow heat release from the AW to the bottom of ice (Hibler et al., 2006; Holloway and Proshutinsky, 2007).

Model forcing and validation: Observational data analysis is needed for model calibration and validation. In particular, small errors in ice parameters stemming from errors in atmospheric forcing can translate into serious errors in ocean variables. Hunke and Holland (2007) compared three forcing data sets in global ice-ocean simulations over 20 years, finding that minor changes to forcing resulted in substantial discrepancies in the simulations, not only in the ice parameters, but also in the deep ocean (e.g. the sense of AW circulation could reverse). Knowing the range of model errors due to forcing fields will allow for more accurate evaluation of the range of errors associated with the internal model physics. Among sources for atmospheric and oceanic data for model forcing and validation there are digital atlases (NCAR/NCEP, ERA-40, NP drifting stations, EWG (1997, 1998, 2000)), current meters compilation (Holloway, 2008) and more than 500,000 hydrographic stations in AARI archives. As well, JPL will provide results from Synthetic Aperture Radars and ICESat to help validate high-resolution modeled sea ice.

Process/climate change studies

These activities address Goal #2: "Investigate variability of the Arctic Ocean and sea ice at seasonal to decadal time scales, and identify mechanisms responsible for the observed changes." The major strategy for these studies will be the investigation on how different mechanisms and processes influence variability of the ocean and ice integrated parameters: ice area, ice extent, ice volume, major ice and ocean circulation patterns or regimes, vertical T-S structure (parameters of major ocean layers), heat and freshwater content. These studies will help improve models and allow AOMIP to investigate processes using model results and observations. This research will be based on the results of 50- and 100-year experiments and on a set of experiments specifically designed for some of these studies and described below.

Fresh water and heat: This research will attempt to answer the fundamental questions: How does fresh water/heat enter the Arctic Ocean system? How does it move about including undergoing phase changes? How does it finally exit the system? First, groups responsible for this activity (Table 2) will evaluate how well models can reproduce pan-Arctic freshwater and heat budgets by comparison of model outputs budgets of Serreze et al. (2006, 2007). We anticipate that most (but perhaps not all) models will achieve freshwater and heat balance in the upper layers including the AW after several decades. How these balances are actually achieved will provide insight into model physics. Second, AOMIP will investigate how well the models can reproduce the basic water mass structure of the Arctic Ocean. For example, Fig. 1 (left) shows a comparison of modeled late winter sea surface salinity within the Beaufort Gyre from an early AOMIP study (Steele et al., 2001). The result indicates a salty bias in this variable which had not been clearly shown until then. Addressing causes of this bias, Zhang and Steele (2007) show how the magnitude of numerical vertical mixing can affect salinity structure within the Beaufort Gyre (see also the discussion above).

Sea-level variability and change: Proshutinsky et al. (2001b, 2007b) reported that the majority of AOMIP models for 1954-1989 had notable difficulties in reproducing Arctic sea-level variability. The major cause of this problem was the omission of sea-level variability associated with changes in atmospheric pressure and water volume fluxes from river runoff. Model outputs from 50- and 100-year models runs will be used to evaluate rates of Arctic Ocean sea level change (see Proshutinsky et al., 2007b for approach). Among science questions of sea-level rise we will attempt to understand inconsistencies in the behavior of Arctic sea-level (rises) and the Arctic Oscillation index (low and stable) in the last decade despite the previous 40-year excellent correlation (Figure 1, right).

Sea ice: With record minima in 2007 ice concentration, the fate of ice is clearly a critical question for climate research. Our focus in this component is to evaluate competing explanations for the recent reductions in ice concentration/extent. If Serreze et al. (2003) are correct ice extent should be significantly different among the AOMIP models that, with the same forcing, have different Atlantic Water (AW) circulations and hence different patterns of heat loss to the surface. This difference would be extreme between the Barents/Kara Sea area and the area along northern Greenland/Canadian Archipelago. If differences in ice are attributable, at least in part, to different AW circulation, it may offer one explanation for the greater variance in modeled ice than in the observations as shown by Johnson et al. (2007). The major instruments for these studies will be numerical experiments with and without ice dynamics, with and without thermodynamics, and with different forcing.

Atlantic water: Circulation of AW in the Arctic has been an especially important subject of modeling studies because it is important to (i) confirm or correct the circulation schemes inferred from observational data; (ii) test and validate the ability of models to capture the boundary currents and circulation of the deep layers of the Arctic Ocean; (iii) elucidate the nature and impacts of the cyclonic versus anticyclonic AW flow regimes in the Arctic Ocean (e.g. Proshutinsky and Johnson, 1997); and (iv) determine the underlying reasons why AW penetrates the Arctic basin in the first place. AOMIP simulated

AW circulation in the Arctic basin differs in intensity and sense of rotation from model to model. In an attempt to understand such discrepancies and inconsistencies, AOMIP has overseen a series of coordinated modeling experiments, identifying numerous factors influencing AW behavior. However, there are still several competing hypotheses, for example, from Holloway's idea (Holloway et al., 2007) that AW circulation is stable and does not change to the Karcher et al. (2007) findings that AW circulation pulsates and can change sense from time to time. There are difficulties associated with each of the above proposed mechanisms and better understanding of the primary driving mechanism for the flow of AW into the Arctic, and how it will vary under changing climate conditions (wind, ice cover, precipitation, heat loss) is greatly needed and will be a primary focus of AOMIP studies.

Tides: Holloway and Proshutinsky (2007) have introduced parameterizations for tidal influence on ocean mixing and on ice dynamics in a 3-D coupled ice ocean model. They have shown that tidal forcing leads to an enhanced heat loss from AW and ice thinning along continental slopes where tides dominate other motions. On the other hand, this thermodynamic effect competes with net ice growth during rapid openings and closings of tidal leads. They recommended testing their conclusions with a model where tides are included directly without parameterizations. Several AOMIP groups (Table 2) will lead this investigation by running their models with and without tides for at least 50 years to understand the tidal role in the shaping of Arctic climate. We expect that the model results between these cases will significantly differ at the continental slope and ridges, around islands, and in the Canadian Archipelago.

Interaction of global ocean with the Arctic: AOMIP global models will conduct experiments to examine interactions of the Arctic Ocean with global changes. Major concerns will include change via signals brought with AW and Pacific water (PW). AW circulation within the Arctic Ocean was a major topic of recent AOMIP studies (see above); ongoing AOMIP efforts will focus on signals penetrating to the Arctic with AW and on how both outflowing AW and PW affect the North Atlantic and global ocean, including the potential for "freshwater catastrophes".

Summary

The coordinated community approach to the investigation of Arctic Ocean variability is the only way to assess the degree of uncertainty in results and conclusions made by different modelers, scientific groups or institutions. AOMIP is an important and unique component of present-day Arctic studies because it improves our understanding of oceanic and sea-ice processes. From this view point, the most significant AOMIP contributions will be: development of regional and improvement of global climate models; identification of model errors and causes of these errors and model discrepancies and recommendations for improvements of existing regional coupled ice-ocean models and GCMs by implementing new physics and parameterizations for Arctic processes. Within these activities, an important contribution will be an assessment of the state and variability of Arctic sea ice and ocean parameters for 1900-present.

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Impact of different Bulk Parameterization schemes of air–sea fluxes on oceanic heat content in the Tropical Indian Ocean

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1. Introduction

Understanding the variability of oceanic heat content and its anomalies is quite important in studying the temporal evolution of the coupled ocean-atmosphere system. It is one of the important parameters that leads to cyclogenesis. In the tropical Indian Ocean, especially the Bay of Bengal, which is frequently struck by tropical cyclones, heat content plays a key role in determining the conditions favourable for such events. Due to the lack of in-situ observations over the oceans, estimation of heat content (or any other oceanic parameter, say mixed layer depth, sub-surface isotherm depth etc.) has been a problem. More recently with the deployment of Argo profiling floats (Argo Science Team 2001) the observation network in the world oceans has improved, but still, complete 3-dimensional oceanic fields from these floats are not available on regular basis. Ocean general circulation models therefore, play a key role in estimating these fields. However their performance in turn depends upon the atmospheric forcings and the parameterization schemes used in the model. In the present study we have made use of two different air-sea flux bulk parameterization schemes in an ocean general circulation model and examined their impacts on the simulated oceanic heat content of the Indian Ocean.

2. Experimental setup

The model used in the present study is the Modular Ocean Model (Pacanowski and Griffies, 2000) version 3.1 (MOM-3) which has been set up for the global domain excluding polar regions (80°S - 80°N) with variable horizontal resolution of from 0.5 degrees in the Indian Ocean to 2 degrees in the rest of the oceans. There are 38 levels in the vertical with 8 levels in the upper 40 meters. The bottom topography is based on 1/12° by 1/12° resolution data from the U. S. National Geophysical Data Centre. Monthly climatological river discharge data for 3000 rivers were downloaded from the UNESCO site and used.

Using climatological temperature and salinity (Levitus 1982) the model was spun up from rest for 20 years forced by climatological winds (Hellerman and Rosenstein 1983) and with restoring boundary conditions for SST and sea surface salinity. Later the model was run for the two-year period (2003-2004) forced with scatterometer winds from QuikSCAT. Two sets of simulations were carried out. In one experiment (E1) we used the parameterization scheme of Large and Pond (1982) to compute the exchange transfer coefficients of momentum, sensible and latent heat fluxes, while in the other experiment (E2) the parameterization scheme proposed by Kara et. al. (2000) was used. Latent and sensible heat flux components are computed using the model's SST. Daily heat content up to the 20° isotherm depth was computed from both the experiments. This was then compared with the climatological values obtained from Levitus temperature profiles. Heat content derived from model simulations was also checked against those obtained from Argo profiling float measurements collected during 2003-2004.

3. Results

The model was able to reproduce the climatological patterns of heat content ($x10^7$ J/m^2) for the tropical Indian Ocean in both the experiments with E2 simulations closer to climatology. However both the runs showed an underestimation in heat content especially in the Arabian Sea. More than the mean pattern, regions of strong heat content variability are important

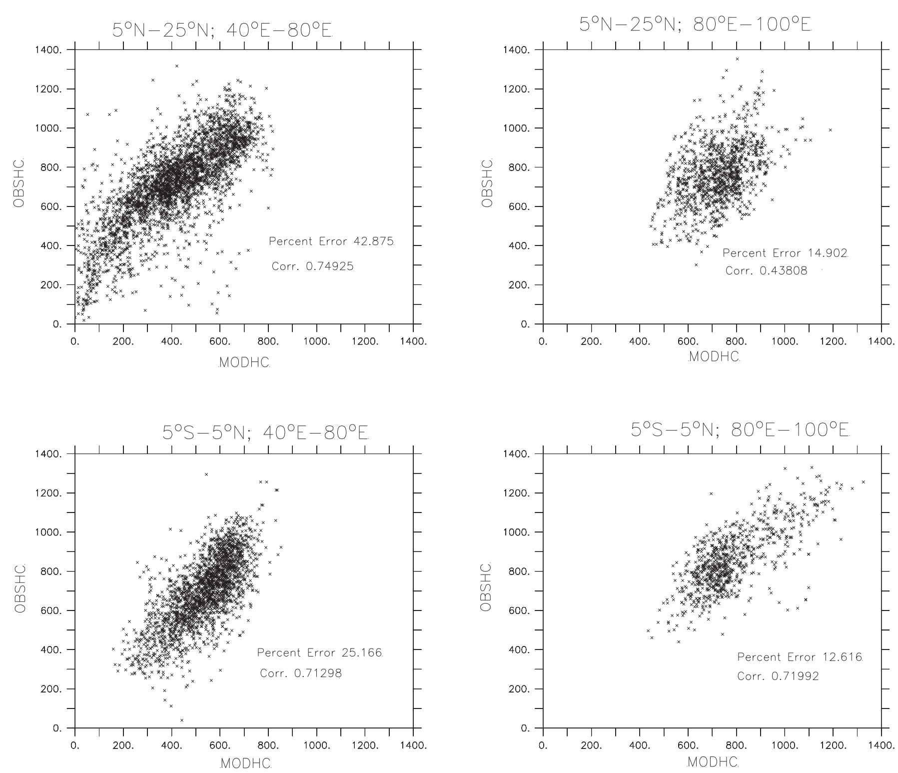

Figure 2. Scatter plots of model (E1) simulated and observed heat content for four different regions in the Indian Ocean

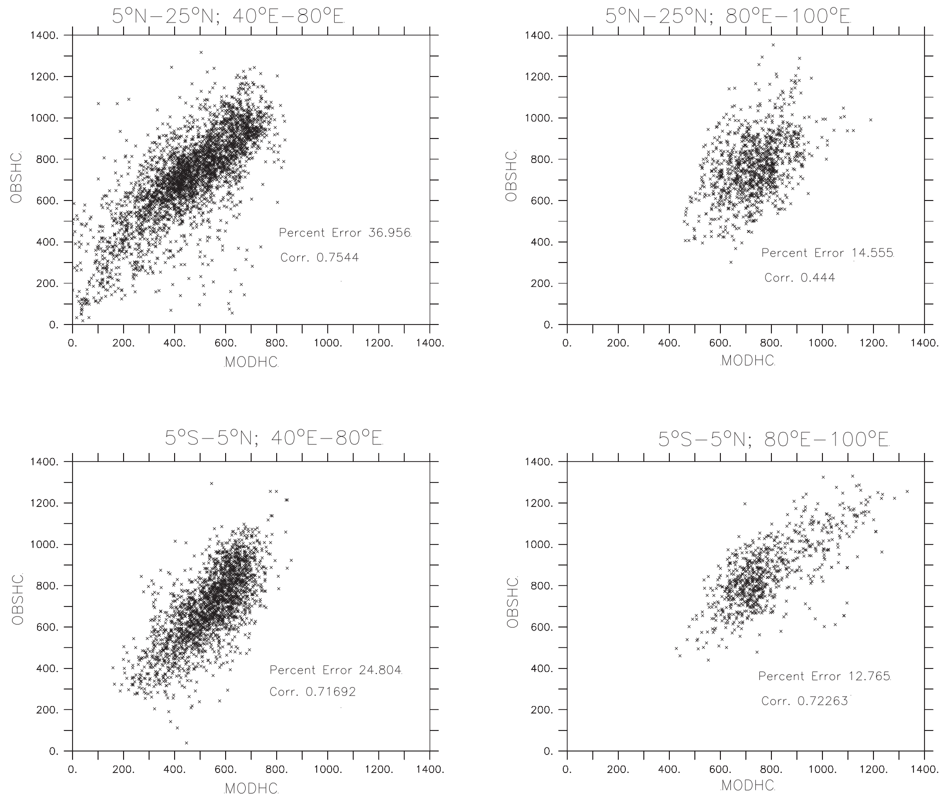

Figure 3. Same as figure 2 but for E2.

for air-sea exchange processes. Figure 1 (page 21) shows the standard deviation of the heat content computed from experiment E2 over the two-year (2003-2004) period. Strongest variability centers are in the eastern equatorial Indian Ocean, the southeast Arabian Sea and along the eastern boundary of the Bay of Bengal. These regions acquire significance as they play important role in Indian Ocean dipole events (eastern equatorial region), summer monsoon dynamics (southeast Arabian Sea) and cyclone formation (Bay of Bengal). A detailed study connecting the heat content variations and air-sea exchange processes will be taken up separately.

A detailed comparison using co-located (~9500 profiles) Argo observations for the same period was made. Four regions viz., Arabian Sea (5°-25° N and 40°-80° E), Bay of Bengal (5°-25° N and 80°-100° E), Somali (5° S-5° N and 40°-80° E) and the eastern equatorial Indian Ocean (5° S-5° N and 80°-100° E) were selected for comparison. Performance of the two bulk formulations, E1 and E2 in simulating heat content against heat content derived from Argo floats are shown in Figures 2 and 3 respectively. The y-axis represents observation and x-axis model heat content. The scatter is similar in three regions except for the Arabian Sea where the Kara et. al. (2000) formulation (E2) shows a better performance (8 % improvement over E1). Although E2 results in improvement, yet some amount of bias in simulated heat content still persists in the Arabian Sea. Correlations between E2 heat content and Argo heat content are better than 0.7 except for the eastern equatorial Indian Ocean, where correlation is 0.44.

4. Conclusions

The present study has examined the impact of two different air-sea bulk parametrization schemes on 20°C isotherm heat content obtained from ocean general circulation model simulations. The main findings can be summarized as follows:

- The model performs reasonably well in simulating heat content in the tropical Indian Ocean with two parameterization schemes.
- The two schemes did not lead to very different results as regards to heat content simulations, albeit Kara et al. (2000) shows slight improvement in the simulation in the Arabian Sea. The bias in this region was also reduced with the Kara et al (2000) formulation.
- This is a preliminary analysis and we intend to do detailed and rigorous analysis on the impact of different bulk formulations on ocean model simulations.

Acknowledgements

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Report from the CLIVAR Working Group on Ocean Model Development (WGOMD)

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The 7th Session of the CLIVAR Working Group on Ocean Model Development (WGOMD) was held on the 25-26 August 2007, generously hosted by H. Drange of the Nansen Centre (NERSC) and the Bjerknes Centre (BCCR) in Bergen Norway. This meeting focused on the major issues that the panel needs to make progress on, namely the CORE experiments and ocean model evaluation metrics. Reports on regional and institutional activities from individual WGOMD members are available on the meeting web page (http://www.clivar.org/organization/wgomd/wgomd7/wgomd_bergen.php).

The WGOMD meeting was preceded by the Layered Ocean Model Workshop (see the following web page for details: http://oceanmodelling.rsmas.miami.edu/lom/index.html) and the CLIVAR Workshop on Numerical Methods in Ocean Models (http://www.clivar.org/organization/wgomd/nmw/nmw_main.php), that is summarised below. The WGOMD meeting coincided with the Inaugural Meeting: Southern Ocean Physical Oceanography and Cryosphere Linkages (SOPHOCLES) (http://clic.npolar.no/theme/sophocles.php). WGOMD joined part of a session of the SOPHOCLES meeting and contributed some presentations outlining the CORE experiments. The SOPHOCLES community is interested in the CORE-II framework, particularly run at high resolution, though processes of interest such as water mass formation, are sensitive to details of the experimental protocol, in particular salinity restoring and coastal run-off. The question was raised of how restoring is applied under sea ice.

Review of WGOMD activities

The terms of reference of WGOMD have been updated through the removal of the qualifier on the first term of reference that previously limited WGOMD activities in stimulating the development of ocean models for research in climate and related fields to decadal and longer timescales at global scales. This focus on longer, global timescales originated from WGOMD's original role as support for WGCM. WGOMD will extend its activities to shorter and smaller spatial scales including regional and coastal problems, as well as involvement in ENSO-related issues.

A central mission of WGOMD is to facilitate the maturation of ocean models, and the use of ocean models in well defined and reproducible ocean modelling simulations. WGOMD aims to realize this mission by (a) providing pedagogical peer-review survey papers that document models and the experimental design of simulations, see for example Griffies et al. (2000), and (b) by organizing topical workshops that bring elements of the oceanography community together to discuss research and development areas relevant to increasing the scientific integrity of models and their simulations.

Attendees of the WGOMD Panel Meeting, Bergen, Norway.

Realizing this mission (or some aspect of it) allows WGOMD to provide scientifically based advice to other CLIVAR panels and to WGCM.

Summary of Workshop on Numerical Methods in Ocean Models

Prior to the WGOMD panel meeting, the WGOMD, with assistance from the Layered Ocean Model (LOM) group, organized the workshop "Numerical Methods in Ocean Models" on August 23-24, 2007 in Bergen, Norway.

The evolution of ocean models is prompted by a growing range of high profile scientific and engineering applications. These applications range from refined resolution coastal and regional modelling forecast systems, to centennial-millenial global earth system models projecting future climate. Groups worldwide are working to improve the integrity of ocean models for use as tools for science research and engineering applications. This work involves a significant number of fundamental questions, such as what equations to solve, which coordinate system to solve the equations in, what horizontal and vertical mesh is appropriate, what physical parameterizations are required, and what numerical algorithms allow for computational efficiency without sacrificing scientific integrity. Furthermore, given the increasing size of many applications, as well as difficulties of doing everything in just one group, there is a growing level of collaboration between diverse groups. This collaboration spans the spectrum of algorithm sharing to the merger of previously disparate code bases.

The numerical methods workshop aimed to foster the maturation of ocean models by supporting enhanced collaboration between model developers. It did so by bringing together nearly 100 of the world's top ocean model developers and theoreticians. Presentations were given throughout each day, with plenty of opportunity for interactions, debate, and networking. The workshop emphasized fundamentals of ocean model numerical methods and physical parametrizations. The relevance of a particular approach gauged by its ability to satisfy the needs of various applications. This workshop provided a venue for participants to educate one another on the latest advances in ocean model development.

Coordinated Ocean-ice Reference Experiments (COREs) Overview

COREs provide benchmark experiments for global ocean-ice models, and a step towards developing an Ocean Model Intercomparison Project (OMIP). The CORE-I proof of concept project includes seven international modelling groups and consists of three ocean model coordinate classes (geopotential, isopycnal and hybrid). A peer-review paper is currently in preparation illustrating CORE-I (see below) results with the seven ocean-ice models each run for 500 years (Griffies et al., 2008).

Attendees at the Layered Ocean Model Group Workshop "Numerical Methods in Ocean Models" August 23-24th, Bergen, Norway

The current COREs do not constitute Ocean Model Intercomparison Projects (OMIPs) as WGOMD is not prepared to formally sanction the present forcing dataset protocols until the community has had time to provide feedback. This means that the set of COREs outlined below are research projects that are voluntarily conducted by interested scientists and there is no formal oversight committee or data repository arrangement in place. This does not prevent the project from eventually evolving into an OMIP.

Ocean-ice model experiments are useful since they are less costly than fully coupled experiments, they can be used in hindcast mode to reproduce the history of ocean and ice variables and hence help in the interpretation of observations, they allow for the understanding of processes in the absence of biases introduced by the atmospheric model and hence potentially give superior representations (compared to the ocean component of a coupled model) of key physical, chemical and biological processes and so help in model development.

The question of the usefulness of CORE relative to coupled experiments received considerable attention. On the one hand, running CORE-type experiments facilitates testing ocean parameterisations in a framework that is isolated from the sensitivities generated by running in coupled mode. On the other hand, there is the view that testing multiple ocean models is less beneficial than assessing changes in the context of coupling to an atmosphere model.

Three CORE experiments have been endorsed by WGOMD, and these are outlined below. The CORE framework is not limited to these three experiments.

CORE-I

This experiment aims to investigate the climatological ocean and sea-ice states realised through multi-centennial simulations forced by idealised repeating normal year forcing that has been derived from 43 years of interannually varying forcing, retaining synoptic variability with a seamless transition from 31 December to 1 January (Large and Yeager, 2004).

After being initially proposed in 2004, CORE-I has reached a critical mass with a community-wide proof of concept approval and seven ocean-ice models (including geopotential, isopycnal and hybrid coordinate models) that have been run for 500 years with the repeat 'normal year forcing' of Large and Yeager (2004). The experiment has yielded a wide variety of results, with as many questions raised as answered. Broad comparison projects such as this achieve much in this way by raising questions, which then motivate further research. Without such a comparison, questions would remain unasked, and thus unanswered. A peer-review paper with 24 authors (Griffies et al., 2008) is under review at Ocean Modelling.

Performing 500 year runs highlighted that the stability of Atlantic MOC was an issue for some models in CORE-I, causing the project to falter for sometime. Some groups were not able to maintain a quasi-stable MOC for the CORE-I multi-centennial simulations without applying a non-trivial salinity restoring, also necessary to damp drifts in deep water mass properties. The participating groups were given the freedom to choose their own salinity restoring depending on each model's sensitivity. Initial results on the sensitivity of the MOC solution to model resolution indicate that models with a finer horizontal resolution (in the North Atlantic Ocean) appear to be less sensitive to details of the SSS restoring.

CORE-II

This experiment aims to investigate the forced response of the ocean in hindcast mode. The experiment will be forced by the interannually varying dataset from 1958-2004 (soon to be updated to 2006) of Large and Yeager (2004).

The initalisation of the CORE-II hindcast simulation is the key issue that needs to be addressed by the CORE-II protocol, particularly if more than the evolution of the upper ocean is to be analysed. Models can be initiated sub-optimally from the existing reanalysis period starting in the 1950s and cycling through the simulation multiple times, though still having to ignore the analysis of the first few years of the final realisation because of adjustment. An additional limitation of this approach is that the existing reanalysis period is biased to the steady increase in the NAO index between the mid-1960s and mid-1990s.

Model drift, particularly below 400m, can be removed by subtracting the trend from a climatologically forced control simulation, assuming that the system is linear.

CORE-III

This experiment aims to investigate the response of an ocean forced with normal year forcing (as in CORE-I) to a freshwater perturbation resulting from increased melt water run-off distributed around the Greenland coast. This experimental design with a hosing perturbation of 0.1Sv, proposed by Gerdes et al. (2005, 2006), is motivated by possible increases in Greenland melt water that could occur as a result of anthropogenic global warming. This runoff prescription contrasts to the practice of applying a freshwater perturbation uniformly over a North Atlantic box, as done with the Coupled Model Intercomparison Project (CMIP) for use in paleo-studies. The alternative runoff prescription from CORE-III provides a more realistic distribution of a water flux anomaly relative to the pathways of the North Atlantic meridional overturning circulation, and so can be useful to understand transient responses of the ocean. The proposed perturbation is slightly stronger than the average increase in meltwater flux from Greenland estimated over the next 500 years and it is kept constant during the 100 year experiment, which is unlikely to be the case in reality.

The experiment would be spun up with CORE-I normal year forcing, with the last 100 years repeated with the freshwater perturbation. Continuing the simulation for a recovery period would be optional. The choice of surface boundary condition remains open and could be coupled or partially-coupled, for example by an anomaly-EBM. WGOMD members are interested in exploring the CORE-III design.

Ocean Model Evaluation

The fourth term of reference of WGOMD states that one of the responsibilities of this working group is "to stimulate the validation of ocean models when used in stand alone mode and as part of a coupled ocean-atmosphere model, using oceanographic data and other methods." There is a need for a community-wide comprehensive best practice for the overall comparison and evaluation of models that is not solely based on 'favourable' diagnostics.

WGOMD Repository for the Evaluation of Ocean Simulations (REOS): WGOMD is planning to develop a website hosting a peer-reviewed clearing house on how ocean models can be systematically assessed with respect to observed datasets to monitor simulation skill, characterize the structure of model biases, assess the impact of numerical/physical choices and guide further investigations. The website will share methods, views on best practices and observational dataset quality with the wider modelling and data assimilation community. Different modelling groups already have extensive model evaluation practices and experience with comparing model simulations to observed data. The CLIVAR GSOP data synthesis community is also in the process of organizing the evaluation of synthesis products and PCMDI has plans to develop a website on climate model evaluation.

Metrics can only be defined as being useful if they are relevant for application, for example, as benchmarks to compare model development or to help understand ocean variability and mechanisms in models. There are different requirements depending on the focus of the assessment. Metrics will be classified according to priority and complexity. Metrics need to be adaptable to cope with differences that arise from analyzing different model resolutions, such as calculating transports through straits in models with different degrees of resolution. Quantitative methods (space-time collocation, filtering, statistical analyses, etc.) will be identified.

WGOMD Future Direction

WGOMD has previously focused mainly on the science of ocean models. It will now broaden this emphasis towards applying ocean modelling to scientific questions including topics such as decadal prediction and high resolution models. WGOMD continues to support WGCM in understanding climate change, while also supporting the CLIVAR regional basin panels and GSOP. WGOMD also plans to develop links with the WCRP Working Group on Numerical Experimentation (WGNE), having expertise to contribute, particularly in terms of setting model standards for decadal prediction, ocean data assimilation, regional modelling and modelling biogeochemical cycles.

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US CLIVAR Drought Predictability Research Focus

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Long-term (multi-year) droughts have tremendous societal and economic impacts on the United States and many other countries throughout the world. Estimates of the costs of drought to the United States alone range from $6-$8 billion annually with major droughts costing substantially more (e.g., $62B in 1988 according to NOAA). The Dust Bowl drought of the 1930s, which at its maximum extent covered much of the continental U.S. (Figure 1 page 21) is ranked as one of the top domestic weather-related disasters of the 20th century (http://www.weathermatrix.net/education/century/nws.txt). Recent population increases in water-limited regions have increased vulnerability to drought at the same time that climate change projections suggest that drought conditions may become more extreme in the 21st Century, particularly in the southwestern United States (NRC, 2007).

The US is implementing a National Integrated Drought Information System (NIDIS, 2004 – see www.drought.gov), to serve as a dynamic and accessible drought risk information system that provides users with the ability to determine the potential impacts of drought, and the decision support tools needed to better prepare for and mitigate the effects of drought. While NIDIS has a strong focus on the U.S., drought is a global phenomenon, both in terms of the forcing elements and the potential commonality of local processes that operate to make some regions more susceptible to drought than others. As such, confidence in our understanding of drought processes (remote and local forcing, feedbacks, etc.) will be significantly advanced by efforts to properly quantify, analyze and simulate regional drought wherever it occurs. Recent studies (e.g., Hoerling and Kumar, 2003; Schubert et al., 2004; Seager et al., 2005) suggest that such simulations are feasible using current atmospheric models forced by observed large-scale SST anomalies (Figure 2 page 21). There are, however, still major uncertainties about the relative roles of the different ocean basins, the strength of the land-atmosphere feedbacks, the role of deep soil moisture, the nature of long-term SST variability, the impact of global change, as well as fundamental issues about predictability of drought on multi-year time scales.

This general approach to the long-term drought problem requires advanced global modelling and data assimilation capabilities, as well as global observational data sets for monitoring and diagnosing drought, and validating and initializing models. CLIVAR, together with its sister WCRP program, GEWEX, can play an important role in advancing these capabilities and integrating research on long-term drought into operational prediction and NIDIS-type systems.

US CLIVAR has begun two initial projects addressing these issues. The first, DRought In COupled Models Project (DRICOMP) aims to increase community-wide diagnostic research into the physical mechanisms of drought and to evaluate drought simulation in current models. The second is the establishment of a short-term Working Group to facilitate progress on the understanding and prediction of long-term (multi-year) drought over North America and other drought-prone regions of the world, including an assessment of the impact of global change on drought processes. The Drought Working Group is one of several US CLIVAR has initiated (the others being Ocean salinity, MJO simulation and prediction, and Climate interactions in the western boundary current regions). Major aims of these limited lifetime Working Groups include expediting planning and implementation of scientific activities as well as leveraging wider participation in addressing scientific issues of critical importance. They can also facilitate joint activities between U.S. CLIVAR Panels and between U.S. CLIVAR and other national and/or international programs, even to those somewhat beyond the traditional scope of CLIVAR. All Working Groups have international participation through membership and organized workshops.

The DRICOMP and Drought Working Group activities are briefly described in this article. Both are clearly motivated by North American drought, but we recognize the obvious global relevance of drought, and we welcome opportunities to use US research to help promote a true international coordination effort targeting drought.

DRought In COupled Models Project (DRICOMP)

Following the highly successful US led CMEP (Coupled Model Evaluation Project - http://www.usclivar.org/science.html#model) that supported more than 20 projects, the results of which were presented at an international workshop in March 2005, the Drought in Coupled Models Project (DRICOMP), focuses on evaluation of a variety of existing model products to address issues such as the roles of the oceans and the seasonal cycle in drought, the impacts of drought on water availability, and distinctions between drought and drying trends. Small, multi-agency supported supplemental grants were awarded for analysis and evaluation of drought in several previously generated simulation ensembles. These included unforced control runs archived as part of the WCRP CMIP3 multi-model dataset at the PCMDI; multi-model simulations of 20th-century climate and the long stabilized simulations with forcing held fixed at future climate conditions; paleo-climate simulations; the downscaled high resolution model datasets that are part of the North American Regional Climate Change Assessment Program (NARCCAP); coupled model seasonal hindcasts carried out under the Seasonal Prediction Model Intercomparison Project (SMIP2); and others.

Seventeen projects were selected for DRICOMP funding. Most projects address regional drought in North America, but some will explore drought in the Sahel, Asia, S. America, and Africa. The list of projects can be found at the US CLIVAR web site (http://www.usclivar.org/science_status/DRICOMP_awards.html). Similar efforts are also under way as diagnostic sub projects of the WCRP CMIP3 program. The results of the DRICOMP projects will be reviewed at a Drought Workshop to be organized by the US CLIVAR Drought Working Group (see below) in late 2008.

U.S. CLIVAR Drought Working Group

The Drought Working Group incorporates a broad range of expertise including modelling, observations, applications (NIDIS), and diagnostics. A few international representatives contribute as well. The specific tasks of the Drought Working Group are to: 1) coordinate and encourage the analysis of observational data sets to reveal antecedent linkages of multi-year droughts; 2) propose a working definition of drought and related model predictands of drought, 3) coordinate evaluations of existing relevant model simulations, 4) suggest and coordinate new experiments (coupled and uncoupled) designed to address some of the uncertainties mentioned in the introduction (i.e., roles of the oceans, land atmosphere feedbacks, deep soil moisture, etc.), and to contribute to NIDIS-related drought risk assessment; 5) examine the prospects for using land data assimilation products for operational monitoring, assessment and hydrological applications; and 6) organize a community workshop in 2008 to present and discuss the results. The working group will also help coordinate key aspects of the (US) long-term drought research agenda outlined in the recent drought workshop recommendations (e.g. Schubert et al., 2005) and interact with the developing NIDIS program to communicate current drought prediction and attribution capabilities.

As initial products, the Working Group compiled a list of recent papers on drought research, an inventory of accessible data sets for observational studies, and a list of AMIP and coupled model runs that are relevant to drought. These products can be obtained through the Working Group's web page at http://www.usclivar.org/Organization/drought-wg.html. The Working Group has also initiated an effort to develop and compare the definitions and robustness of drought indices (including onset and demise) so that "drought" is quantifiable and verifiable for the purposes of model prediction experiments, drought monitoring and early warning, and facilitating communication between the applications and modeling/research communities.

Lastly, the Working Group has initiated a set of idealized experiments using models at GFDL, NCAR, NASA/GMAO, COLA, NCEP, and LDEO and prescribed forcings (SST variability, warming trends, and soil moisture) hypothesized to influence drought over North America. These forcings are the same for each model and are imposed as a monthly climatology plus a fixed prescribed anomaly. The model integrations are well under way and expected to be complete by Spring 2008. The Working Group will analyze the results from the multiple model runs to identify and compare dynamical mechanisms leading to drought, characterize the drought-like responses to ENSO vs global warming, assess the models' sensitivity to inclusion of deep soil moisture, and other aspects of drought and its predictability. Where possible, the runs (which are all global) will be made accessible to the community.

Results from these simulations will complement the DRiCOMP effort and the many long term coupled model runs that have been analyzed as part of the IPCC climate change assessment process. A workshop will be organized in late 2008 where the results from the Drought Working Group and DRICOMP efforts will be reviewed and discussed.

The long-term drought problem can be an important umbrella issue to bring together the relevant research expertise of international programs such as CLIVAR (with its focus on large scale and ocean-atmosphere coupling), GEWEX (focusing on regional scales and land-atmosphere coupling), and perhaps others in the Earth System Science Partnership (ESSP – www.essp.org) to improve our capabilities to respond to the climate information and prediction needs of the many drought-impacted regions of the world. We look forward to working with the international climate research community to enhance coordination of our activities.

[For further information on US CLIVAR Working Groups, DRICOMP, and other CLIVAR activities in the US, see the US CLIVAR web pages: http://www.usclivar.org]

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The International CLIVAR Climate of the 20th Century Project: Report of the Fourth Workshop

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The International CLIVAR Climate of the 20th Century Project (C20C; Folland et al., 2002) held its Fourth Workshop on 13-15 March 2007 at the Hadley Centre for Climate Change of the Met Office, Exeter, UK. The workshop reviewed progress on coordinated climate simulations and analyses, including new results on 20th century climate variability, and developed plans for new integrated model experiments with various degrees of ocean-atmosphere-land coupling. In keeping with the long-standing theme of the C20C project, forcing data sets, including a new version of the HadISST sea-surface temperature and sea-ice data set were discussed. A new version of HadISST is due for release in 2009, with significantly higher resolution and incorporating (Advanced) Along Track Scanning Radiometer satellite sea surface temperature data. There was also considerable discussion of how to coordinate C20C experiments with related international research programs evaluating the stratosphere's role in climate, and the effects of land use and land cover change on the variability and predictability of climate. The workshop was well attended with 37 participants from 19 different institutions. The workshop web site (http://www.iges.org/c20c/workshops/200703/home.html) includes downloadable copies of the presentations and summaries of the three break-out group discussions. In the following, we summarize the key findings and plans agreed to by project participants.

A total of 32 presentations on various aspects of C20C results were made in the course of the workshop. Besides overview talks on the C20C project, there were presentations on the results of several C20C numerical experiments intended to address the issues of both predictability and attribution of observed climate anomalies over the past century or more, understanding of which is critical to interpret and evaluate the projections of future climate change. Features of the Earth's climate, particularly extremes, such as droughts and floods, the Asian monsoon, monsoons in the Americas and west Africa, and variability of the North Atlantic were all examined. C20C is also concerned with simulating climate trends and so provides an interface with more formal climate change detection projects.

Some of the reported experiments were done in the "traditional" C20C methodology, with atmospheric general circulation models (AGCMs) forced with specified, observed time-varying sea surface temperature (SST) and sea ice as well as greenhouse gases (GHG) and aerosols. The C20C methodology was expanded, as a result of a special meeting in Prague, Czech Republic on 1-3 July 2005, to include the "pacemaker" experimental design. In "pacemaker" runs, a global AGCM is forced by specified SST and sea ice only in a limited region where the interaction between ocean dynamics and atmospheric circulation is likely to produce systematic low-frequency variations. Elsewhere, the feedback between the atmosphere and the ocean is simulated, either by inclusion of a mixed layer model of the upper ocean or with a full coupled general circulation model (CGCM). One region where the coupled ocean-atmosphere system sets the pace for climate anomalies is the eastern tropical Pacific where El Niño and the Southern Oscillation (ENSO) produces quasi-regular excursions of SST and surface winds with a broad spectrum of periods between 4 and 7 years (e.g. Lau and Nath, 2003). One of the workshop break-out groups reviewed plans for further pacemaker experimentation.

Fully coupled experiments by C20C members when compared to observed data are also regarded as part of C20C where their main aim is to investigate coupled mechanisms. A recent example is an investigation of the mechanisms of the Atlantic Multidecadal Oscillation and its climatic influences (Knight et al, 2006 and previous work).

Another extension of the C20C experimental protocol was suggested by the land-surface modelling community interested in assessing the effects of land use and land cover change on climate. By specifying the time-varying state of the global land surface vegetation, these experiments can determine the impact of changes in land cover. A new major international project called, Land Use and Climate, IDentification of robust impacts (LUCID; introduced in Newsletter 4, http://www.atm.helsinki.fi/ILEAPS/), which is being organized under the auspices of International Geosphere-Biosphere Program (IGBP) Integration Land Ecosystem – Atmosphere Processes Study (iLEAPS; http://www.atm.helsinki.fi/ILEAPS/) and the World Climate Research Program (WCRP) Global Water and Energy Experiment (GEWEX), is closely linking its numerical experimental plan with C20C. Another of the workshop break-out groups discussed plans for land use and cover change experiments as well as ways of coordinating with LUCID.

A third break-out group considered the further improvement of forcing data sets, particularly the HadISST SST and sea ice set. Brief summaries of the three break-out sessions are given below.

There was also a presentation and discussion of possible coordination with a related international project for the SPARC initiative (Stratospheric Processes And their Role in Climate; http://www.atmosp.physics.utoronto.ca/SPARC/index.html). In particular, Paul Kushner (U. Toronto) described a new set of experiments being undertaken by SPARC on Dynamics and Variability. There has been increasing interest in the stratosphere community about the possibility of downward propagation of signals from the stratosphere to the troposphere and even to the surface. In the context of C20C, Scaife et al (2005) showed this idea was important for understanding the climatic effects of the North Atlantic Oscillation on decadal time scales. The new experiments, to be conducted in AGCM and CGCM simulations, are expected to evaluate the consequences of poor resolution of stratospheric dynamics in such models and to determine how the stratosphere might influence the coupled ocean-atmosphere system, both in terms of current climate variability and the potential role of the stratosphere in future climate change. A set of experiments was proposed that include identical model runs with and without a resolved stratosphere ("high-top" and "low-top" runs), and stratospheric modelling groups are encouraged to conduct interactive stratospheric chemistry runs using the climate forcings datasets available from the C20C project (http://grads.iges.org/c20c/c20c_forcing/home.html).

Pacemaker Experiments

Several groups have already undertaken pacemaker experiments, primarily with the eastern tropical Pacific region. Several studies have examined the relationship between ENSO and the Asian monsoon, but it is not clear if a consensus on the relationship has emerged from the ensemble of model simulations. A few experiments have also been done with specified north Atlantic SST, but, again, no clear conclusion has been drawn. The break-out group that reviewed pacemaker progress to date, found that there are a number of outstanding questions that need to be addressed with the methodology, including investigation of other specified-SST regions, inclusion of ocean dynamics, comparison with traditional C20C runs as well as runs with specified climatological SST, inclusion of uncertainty in the specified SST, and possible extensions of the method to decadal predictability and climate change issues. The break-out group recognized the inherent limitations of the first generation of pacemaker experiments. In particular, the procedures for prescribing SST anomalies in these experiments do not take full account of the two-way interactions of the atmosphere-ocean system in various regions of interest. Moreover, these experiments do not address important issues related to the origin of the SST anomalies themselves. Novel coupling techniques and experimental designs are needed to delineate the roles of various feedback processes in climate variability on various time scales.

Land-Surface Simulation Experiments

The problem under investigation is to determine the changes in the land surface that can and do drive climate change, with a focus in the near term on the west African monsoon and persistent droughts such as that in the Sahel in the 1970s and 1980s and in North America during the Dust Bowl years. A set of experiments was defined that address these foci. One set of runs will be done with and without the observed changes in land use in conjunction with the full set of forcing functions (SST or fully coupled, GHG, etc.). Another set duplicates the first set, but with land surface changes only in selected regions to gauge the local and remote effects. A third set of simulations is planned with idealized land surface scenarios only in west Africa to consider possible origins of the persistent drought in the Sahel.

One aspect that is especially exciting about these experiments is that the LUCID experimental plan is explicitly linked to the C20C protocol. In fact, a comprehensive list of experiments has been developed for the LUCID project in which several of the planned model simulations are C20C model integrations. The prospects for coordination between C20C and LUCID provide a basis for leveraging the work done in each project. Currently, eight of the C20C modelling groups have agreed to participate in the joint experiments.

Forcing Data Sets

Plans are in place for the development of the next generation HadISST2.0 SST and sea ice observational data set, expected to be released in 2009. The group at the Hadley Centre is placing emphasis on reducing biases, increasing resolution in more recent decades and estimating uncertainties, primarily in the SST field. In the satellite era, development of HadISST2.0 will benefit from a close working relationship with the Global Ocean Data Assimilation Experiment High-resolution Sea Surface Temperature Pilot Project (Donlon et al, 2007). Other external forcing data were also discussed, and it was strongly recommended that, for those groups whose models have the capability, detailed aerosol treatments be used. The group also recommended that the standard set of forcing data be reviewed for all future C20C simulations, including SST and sea ice, GHG, stratospheric ozone, and stratospheric volcanic aerosol.

Future Plans for C20C

Intercomparison of the ability a number of the C20C models to reproduce key features of twentieth century climate variability and change when run in classical C20C mode are under way and are planned to be submitted for publication in early 2008.

As described above, the future C20C simulations are intended to address questions raised in previous rounds to help better understand mechanistic questions relating to seasonal and decadal predictability and forecasting, and to prepare to contribute to the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC). Experimental designs are in place for more detailed pacemaker simulations and land use change experiments. There are already strong ties in place to the CLIVAR Working Group on Seasonal-to-Interannual Prediction (WGSIP) and now to the LUCID project. A C20C representative is now also on the SPARC committee of the Dynamics and Variability Coupled Stratosphere-Troposphere System project (SPARC Newsletter 29, July 2007).

A special session on C20C is planned for the 82nd Annual Meeting of the American Meteorological Society in New Orleans on 22-23 January 2008. A fifth C20C workshop will take place in late 2009, tentatively in Australia..

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The Ocean Component at ECMWF: Towards a seamless prediction system

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Although originally implemented as part of the operational seasonal forecasting system in 1997, the scope of the ocean component at ECMWF has been steadily widening with time. It is now also used for the operational monthly forecasting system (since October 2004), and in the near future it will be part of the medium range forecasting system. On the longer time scales, the ocean component is also required for the decadal forecasts conducted within the ENSEMBLES project. The ocean model is an integral part of both the forward model (coupled ocean-atmosphere-land-wave system), and the ocean data assimilation system needed to provide the ocean initial conditions for the coupled forecasts. The coupled forecasts usually require calibration, achieved by performing a series of hindcasts for a sufficiently long historical record. The ocean initial conditions for the calibrating hindcasts are obtained by conducting an historical ocean reanalysis, which has the additional value of providing information about the ocean variability at different time scales (from days to decades).

The Ocean Analysis System

The ocean data assimilation system is based on the HOPE-OI scheme: The first guess is given by forcing the HOPE (Hamburg Ocean Primitive Equations) ocean model with daily fluxes of momentum, heat, and fresh water, while the observations are assimilated using an Optimal Interpolation (OI) scheme. The HOPE ocean model (Wolff et al., 1997) uses an Arakawa E grid horizontal discretization and variable bottom topography. Several modifications to the original code were introduced in the operational configuration in 2001: The horizontal resolution is 1^o x 1^o with equatorial refinement (i.e., the meridional resolution increases gradually towards the equator, where it is 0.3^o in the meridional direction). There are 29 levels in the vertical, with a typical vertical thickness of 10 meters in the upper ocean. The vertical mixing is based on Peters et al., (1988). The barotropic solver, originally implicit, was made explicit as described in Anderson and Balmaseda (2005).

A new ocean analysis system (ORA-S3) was introduced operationally in August 2006. The ORA-S3 system has several innovative features, including an on-line bias correction algorithm, the assimilation of salinity data on temperature surfaces, and assimilation of altimeter-derived sea level anomalies and global trends. A detailed description of the analysis system is provided in Balmaseda et al (2007a). Also a selection of historical and real-time ocean analysis products can be seen at www.ecmwf.int/products/forecasts/d/charts/ocean/.

The first-guess is obtained from integrating the HOPE ocean model from one analysis time to the next, forced by daily ERA40/OPS fluxes (ERA40 fluxes from the period January 1959 to June 2002 and NWP operational analysis thereafter). The representation of the upper ocean interannual variability is improved when using the ERA40 wind stress (Uppala et al., 2005), although the stresses are biased weak in the equatorial Pacific. The fresh water flux from ERA-40 (Precipitation-Evaporation, denoted P-E) is known to be inaccurate. ORA-S3 uses a better but by no means perfect estimate, obtained by 'correcting' the ERA-40 precipitation values (Troccoli and Kållberg, 2004). The surface salinity is relaxed to climatological values with a time scale of 1 year.

When designing a data assimilation system for seasonal forecasts several considerations need to be taken into account. It is important to represent the interannual/decadal variability in the ocean initial conditions, and therefore strong relaxation to climatology is not recommended. On the other hand, in order to avoid spurious trends and signals due to the non-stationary nature of the observing system, the ocean analysis mean state should not differ too much from the observed climate. It is also important to avoid large initialization shocks in the coupled model, which may damage the forecast skill. In ORA-S3 we have tried to strike a balance between the above requirements: the weight to observations has been reduced and the relaxation to climatology is considerably weak (10-years time scale). This has been possible because an additive bias correction has been included (Balmaseda et al., 2007b).

The ORA-S3 consists of an ensemble of five simultaneous ocean analyses that contribute to the creation of the ensemble of probabilistic forecasts. In addition to providing initial conditions for forecasts, the ocean reanalysis is an important resource for climate variability studies (Balmaseda et al., 2007c).

The ocean model in the coupled system: current practice and limitations.

In coupled mode, the ocean model provides information about the SST and the ocean current to the atmosphere and wave model, which return fluxes of heat, momentum and fresh water flux. The coupling is done daily in the seasonal forecasting system and hourly in the monthly forecasting system. There is not a dynamical ice model. Instead, the ice concentration is persisted during the first 15 days, after which damped persistence is used for an additional 15 days, when climatological values are used. To produce the coupled forecasts, the coupled model is initialized with atmospheric and ocean analyses, and integrated forward in time for 7 months in the case of the seasonal forecasts (once a month) and 32 days for the monthly forecasts (currently once a week). No relaxation or flux correction is applied during the forecasts, which are corrected a-posteriori using a fix set of calibrating hindcasts.

Currently, the monthly forecasting system uses the same ocean model configuration as the seasonal forecasting system. Vitart et al. (2007) and Woolnough et al. (2006) have shown the benefits of having an active ocean in forecasts of the Madden Julian Oscillation (MJO) at monthly time scales. Their work also demonstrates that a better representation of the mixed layer process is needed to improve the predictions of the MJO. In particular, they highlight the importance of the diurnal cycle and its rectification in the representation of the intra-seasonal variability.

Improvements in the representation of mixed layer processes are likely to be important in the skill of seasonal forecasts. Figure 1 (page 22) shows the seasonal prediction of mixed layer depth (MLD) in the north subtropical Atlantic from April and June initial conditions (red curves). The forecasts starting from April systematically overestimate the MLD (compared with the analysis in black). The forecasts initialized in June, when the mixed layer is already shallow, are not biased. Results from ocean-only runs (not shown) suggest that the seasonal bias in the MLD forecasts is partly due to errors of the ocean model.

The lack of a prognostic ice model may be a shortcoming of the current forecasting system. For instance, the significant reductions in Arctic ice cover during the 2007 Northern Hemisphere (NH) summer are not correctly represented in the ECMWF seasonal forecasting system. Experimental results indicate that this anomalous ice cover has an impact on the NH atmospheric circulation. Figure 2 (page 22) shows the Z500 ensemble mean differences between a set of experiments forced by daily varying analyzed ice cover and another set forced by the daily climatological ice cover (as used in the seasonal forecasts). Both sets have been forced by the same prescribed values of SST. The experiments, consisting of 20-ensemble members each, were initialized in May and integrated forward for 5 months. Although the impact in Z500 shows moderate amplitude, it is statistically significant, and in phase with the observed anomaly in the North Atlantic, indicating a potential benefit from proper sea-ice treatment in the seasonal forecasting system. However, the predictability of sea ice anomalies in coupled models is still poorly understood, and it is likely that accurate initialization of sea-ice properties is needed to predict such anomalies a few months in advance.

The a-posteriori forecast correction relies on the validity of the linear approximation, which may not always be appropriate. For instance, there is evidence that warm biases in NINO3 affect the behaviour of the coupled system by reducing the amplitude of the interannual variability in this region. Another potential non linearity is the deep mixed layer bias described above, which will affect the thermal inertia of the ocean and persist the spring anomalies for too long. The excessive persistence of spring temperature anomalies in the North Atlantic is a common error in the DEMETER seasonal integrations (van Oldenborgh, 2007) and needs to be investigated further.

Future plans

ECMWF has adopted the NEMO ocean model (http://www.lodyc.jussieu.fr/NEMO/) as the future ocean component for all the different operational and research activities. Work is needed for the evaluation of the suitable horizontal and vertical resolution and the treatment of the sea-ice. The initialization of the ocean will be done by NEMOVAR, a variational data assimilation system currently under development. The NEMOVAR system, derived from the existing OPAVAR system (Weaver et al., 2005), is a collaborative project between several European institutions (http://www.cerfacs.fr/globc/research/assimilation/assimilation_sheet.html).

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Global Ocean Ship–based Hydrographic Investigations Panel (GO_SHIP) – First Meeting

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One of the action items developed at the November 2005 International Repeat Hydrography and Carbon workshop in Shonan Village, Japan, was to establish a small interdisciplinary advisory group to bring together interests from physical hydrography, carbon, and biogeochemistry to develop guidelines and advice for the development of a globally coordinated network of sustained ship-based hydrographic sections that will become an integral component of the ocean observing system after the end of CLIVAR (post-2013).

Taking these suggestions forward, the IOCCP, CLIVAR, and the SOLAS-IMBER Carbon Group each approved the development of this advisory group in 2006, and earlier this year, the Observations Coordination Group of the IOC-WMO Joint Technical Commission on Oceanography and Marine Meteorology (JCOMM) and the GCOS-GOOS-WCRP Ocean Observations Panel for Climate (OOPC) strongly endorsed its development.

The first meeting of the Hydrography Panel was held in Victoria, BC, Canada on 1-2 November. Over the next 18 months, this group will develop a draft strategy that will be circulated for review and comments in mid 2008, with a final strategy to be published in late 2009. Specifically, the Terms of Reference for this advisory group (the Global Ship-based Hydrographic Investigations Panel, GO-SHIP) are as follows:

i. To develop the scientific justification and general strategy for a ship-based repeat hydrography network, building on existing programs and future plans, that will constitute the core global network, post-CLIVAR; considerations should include:

- a set of basic requirements to define a coordinated repeat hydrography network (e.g., sample spacing, repeat frequency, recommended core measurements, etc.);
- an inventory of existing and planned sections that meet those criteria;
- an assessment of other observing programs that can either contribute to or use hydrography data (e.g., Argo, OceanSITES, GeoTraces, etc.);
- an assessment of data release needs to meet research and operational objectives;
- an inventory of on-going or planned scientific synthesis activities (basin and global) that might benefit from closer collaboration; guidelines for the transition from the CLIVAR hydrographic program to the new system, including sections, data and information management, and synthesis activities.

ii. To develop guidelines for a single global information and data center for ship-based repeat hydrography; and,

iii. To review and provide guidance on the need to update the WOCE hydrographic manual, including a review and update of data quality control issues.

GO-SHIP members include: Chris Sabine (NOAA - PMEL, USA), Nicolas Gruber (ETH, Switzerland), Arne Koertzinger and Toste Tanhua (IfM-GEOMAR, Germany), Bernadette Sloyan (CSIRO, Australia), Greg Johnson (NOAA-PMEL, USA), and Masao Fukasawa (JAMSTEC, Japan).

This first meeting reviewed discussions and decision from the Shonan Village meeting and began drafting sections of the strategy on science goals, temporal and spatial sampling requirements, core and recommended variables, survey lines to be included as part of the sustained system, data release policies, and data and information center needs. The group also reviewed the WOCE hydrographic manual chapters and suggested lead reviewers and authors to update each section. It is envisaged that the advisory group will develop a report within a <2 year period that will be circulated widely for consultation and consensus on the way forward. The final strategy will be presented at OceanObs 09.

The IOCCP (Maria Hood) and CLIVAR (Nico Caltabiano) are providing project office support for the advisory group activities. For more information visit the GO_SHIP site at http://ioc.unesco.org/IOCCP/Hydrography/GOSHIP.html and the International Repeat Hydrography and Carbon Workshop site at http://ioc/unesco.org/ioccp/RepeatHydrog2005.htm.

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There was a full agenda for the 15th CLIVAR Scientific Steering Group (SSG) meeting, the papers and power points for which can be accessed from the SSG-15 webpage at www.clivar.org/organization/ssg/ssg15/ssg15.php. Following a welcome by the Deputy Secretary General of WMO, the meeting initially heard presentations from the three other WCRP core projects and a number of other programmes and activities, including the WMO World Climate Programme (WCP), IGBP IMBER, THORPEX and WGNE and, later, national programme presentations from the US and Japan. Presentations were made by the co-chairs of each of the CLIVAR panels and working groups, including, on the final day, ESF MedCLIVAR. These presentations outlined key progress, future plans and issues arising for the SSG to address. What was clear is that there is substantial momentum and progress on many important scientific topics. Breakout groups with plenary reporting followed these presentations, aimed at providing a review of the directions of CLIVAR science areas against the science area summary papers and CLIVAR "Forward Look" from SSG-14 (see www.clivar.org/organization/ssg/ssg14/ssg14.php).

The SSG also addressed the ways in which CLIVAR is contributing to the WCRP cross-cutting topics of atmospheric chemistry and climate (AC&C), anthropogenic climate change (ACC), climate extremes, monsoons and seasonal and decadal prediction. It was clear that CLIVAR can make, and is making, important contributions in all of these areas, including AC&C. With CLIVAR accepting the responsibility at the meeting of the Joint Scientific Committee of WCRP in Tanzania last April of taking the lead (or co-lead, with GEWEX) in shaping and developing the last four of these activities, it was clear that the cross cuts will need to be an increasing focus for CLIVAR's efforts in the future.

Another important item was a plenary discussion on how CLIVAR should evolve as it moves to it's sunset date of 2013 and the need to define how CLIVAR science will be covered under WCRP post 2013. Current WCRP financial stringencies, outlined by the Director of WCRP, led to an extensive discussion on whether the SSG should make some early changes in the overall panel and working group structure of CLIVAR. The SSG were presented with various organizational options but for the present agreed not to significantly disrupt CLIVAR and its activities, preferring to leave the present structure in place out to the 2010 timeframe at which time a reorganization would be needed to accommodate a final analysis and assessment phase.

With a view to defining the legacy of CLIVAR, the SSG agreed to hold a 2nd CLIVAR Science Conference in 2011 time frame with a final closure meeting in 2013. Part of the aim of the 2011 Conference will be to assess achievements and identify major outstanding science questions. The SSG also recognized the importance of the 2009 World Climate Conference-3 and agreed to seek ways for CLIVAR to input to it. It also endorsed developing plans by the Ocean Observations Panel for Climate and CLIVAR's Global Synthesis and Observations Panel for an OceanObs'09 Symposium.

The SSG heard two science lectures on the 3rd day of it's meeting: "The changing Southern Ocean carbon sink" by Nikki Gruber, ETH, Zurich and "Climate Extremes in a warmer climate – a focus on Europe and the Alps" by Martin Beniston, University of Geneva which were warmly appreciated. Amongst other items the SSG also considered how to improve CLIVAR's outreach. It identified in particular the need to engage on this with WCP, especially in respect of applications of CLIVAR science, and the need to increase CLIVAR's linkages to other science areas such as those represented by IMBER.

A full list of the SSG's Recommendations and Actions can be found on the SSG-15 webpage.

Latest News: WOCE Pacific Atlas Published

The second volume of the series of atlases based on the hydrographic sections worked between 1990 and 1997 during the World Ocean Circulation has now been published. The atlas has large format colour plates of vertical sections, horizontal property maps on both depth and density surfaces and property-property plots (see illustration on page 22). The plotted properties are temperature, salinity, potential density, neutral density, dissolved oxygen, silica, nitrate, nitrite, phosphate, CFC-11, CFC-12, delta3 helium, tritium, delta14 carbon, alkalinity and total carbon. Each atlas contains a DVD of the figures which are also available online at http://www-pord.ucsd.edu/whp_atlas/pacific_index.html (note that the DVD version contains additional figures). The atlas was produced by Prof. Lynne Talley at Scripps Institution of Oceanography with funding from the US National Science Foundation. The first atlas covering the Southern Ocean and produced by Alex Orsi and Thomas Whitworth III (Texas A and M University) was published in 2003. The Indian and Atlantic Ocean volumes will be available later in the year. The printing costs of the atlas series has been funded by a grant from BP. Recipients are asked to pay the mailing costs from regional distribution points in Australia, Canada, Japan, Korea, UK and USA. If you wish to receive a copy please contact Mrs Jean Haynes (jchy@noc.soton.ac.uk).

Full citation.

Talley, L. D., Hydrographic Atlas of the World Ocean Circulation Experiment (WOCE). Volume 2: Pacific Ocean (eds. M. Sparrow, P. Chapman and J. Gould), International WOCE Project Office, Southampton, UK, ISBN 0-904175-54-5. 2007

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