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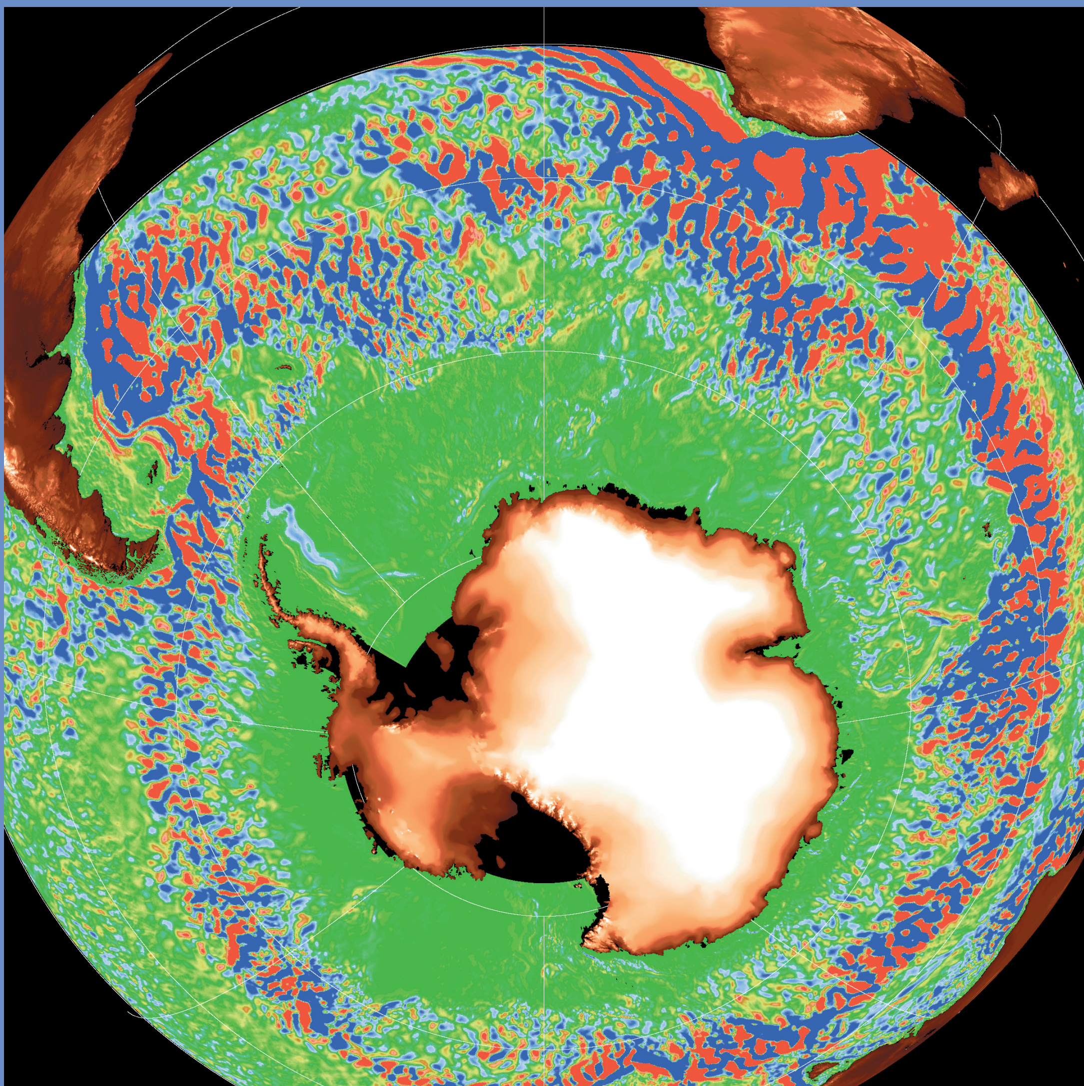
OCEAN MODEL DEVELOPMENT AND ASSESSMENT

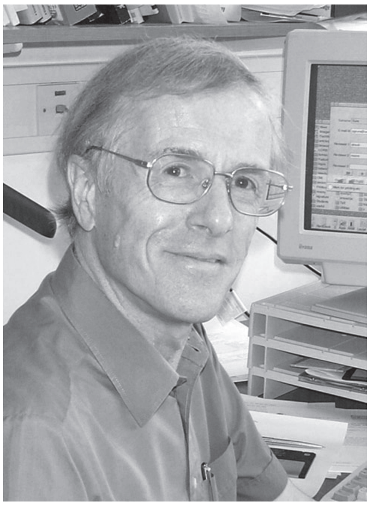


Depth integrated northwards eddy heat transport (100GW per 1/12°x1/12° gridcell) (M.M. Lee, A.J.G. Nurser, A.C. Coward and B.A. de Cuevas. "Eddy advective and diffusive transports of heat and salt in the Southern Ocean". Journal of Physical Oceanography., Vol. 37, No. *5, pages 1376—1393*

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

Editorials



Well, I never thought I would be writing the following words, but I really feel that ocean modelling for climate has come of age. Now we have robust codes with real manuals. I remember being at a meeting about 15 years ago and giving a talk about FRAM, in which I apologised for not showing any gee-whizz slides but would only talk about physics. The next speaker got up and apologised for only showing gee-whizz slides! Now, 15 years later, it would be unthinkable for either a talk or a paper to show only gee-whizz pictures; the field has matured and requires deep physical discussion.

The papers in this issue all show this change in different ways. Some come from large climate centres, and some show the potential for new modelling techniques, but all are only concerned with improving our knowledge of how the climate system works. It has been a pleasure to read them.

Peter Killworth

I am delighted indeed to have Peter Killworth as guest editor of this edition of Exchanges which, as you will have seen, focuses on Ocean Model Development and Assessment and also to have his "seal of approval" of the included articles. As Peter implies, ocean modelling has matured substantially over recent years bringing a new dimension to CLIVAR-related science. In addition to the ocean modelling articles we also include an article on atmosphere coupling of the southern angular mode that also relies on use of an ocean model in a coupled context. CLIVAR's Working Group on Ocean Model Development (WGOMD) will meet in Bergen, Norway from 24-25 August 2007. Amongst other items the meeting will consider its activity in Coordinated ocean and sea-ice Reference Experiments (COREs) and ocean modelling metrics. It will also in part meet jointly with the Southern Ocean Physical Oceanography and Cryospheric LinkagES (SOPHOCLES) project which is just spinning up. The WGOMD meeting will be preceded by a Workshop on Numerical Methods in Ocean Models on 23 and 24 August, reviewing the state of the art and future pathways in this field.

National programmes of course form the basis by which research on CLIVAR is funded and I am also pleased therefore to include an article on the CLIVAR-España network which Roberta Boscolo of the ICPO has been at the centre of. I would like to encourage other articles on national programmes and networks in support of CLIVAR in the future. Roberta also reports in this issue on the CLIVAR Atlantic Implementation Panel meeting that took place in Keil, Germany in March this year.

Looking ahead, the CLIVAR Scientific Steering Group will meet in Geneva, Switzerland from 11-14 September 2007. This year the SSG will be focusing on how to best manage the final 5-6 years of CLIVAR and on what legacy we might leave. Also, the Joint Scientific Committee for WCRP at their most recent meeting (Zanzibar, 26-30 March 2007), assigned CLIVAR the lead on two cross-cutting topics: seasonal prediction and decadal predictability, and the co-lead, with GEWEX, on monsoons and climate extremes. Others cover anthropogenic climate change, atmospheric chemistry and climate, the International Polar Year, and sea level rise These cross cutting areas are likely to be an important element of the overall WCRP plan for the next few years and it is very important that CLIVAR define clearly what its role/contribution to each of these might be. This will therefore provide one of the foci for the SSG meeting the outcomes of which will be reported on in a later edition of Exchanges. Further details of both this and the WGOMD meeting can be found on the CLIVAR website.

Howard Cattle

Cover Image:

Ocean modelling has come a long way over the last few decades. The computational power now available means we can model the global ocean at unprecedented resolutions. The image on the front cover of this issue of Exchanges illustrates one of the new insights arising from high resolution modelling studies. To produce this image, output from NERC's OCCAM (Ocean Circulation and Advanced Climate Modelling project) model has been analysed. The current model has a spatial resolution of approximately 10km horizontally and 66 vertical levels. This global ocean model is routinely run on 512 processors at a time whilst applying atmospheric conditions to the surface of the ocean, which vary every six hours. By careful analysis of a time series of 5 day mean output from the model it is possible to diagnose how and where the poleward transport of heat occurs. The front cover image shows the depth integrated northwards eddy heat transport in the Southern Ocean in units of 100GW per $1/12^o$x$1/12^o$ gridcell. This heat flow is quite considerable; individual grid cells can have as much as 100 GigaWatts of heat passing through them and at some latitudes the eddy transport is the major component of the total heat transport. Based on such evidence the next generation of climate models will have to approximate this transport better (a goal which remains elusive) or include model components that can resolve the processes.

Full details of this work has been published in: Eddy advective and diffusive transports of heat and salt in the Southern Ocean. M.M. Lee, A.J.G. Nurser, A.C. Coward and B.A. de Cuevas. JPO , Vol. 37, No. 5, pages 1376-1393. (2007)

The authors work within the Ocean Modelling and Forecasting group at the National Oceanography Centre, Southampton. Email: acc@noc.soton.ac.uk

Ocean Modelling with MOM

Griffies, S, M J. Harrison, R C. Pacanowski, and T Rosati. NOAA Geophysical Fluid Dynamics Laboratory
Corresponding author: Stephen.Griffies@noaa.gov

The Modular Ocean Model (MOM) is a hydrostatic primitive equation numerical code of use for the scientific exploration of ocean dynamics covering a broad range of space and time scales. In this article, we present an overview of the MOM effort and discuss recent developments and applications.

A Community Model Code

Numerical ocean modelling at NOAA's Geophysical Fluid Dynamics Laboratory (GFDL) originates from Joe Smagorinsky's recruitment in 1962 of Kirk Bryan, then at Woods Hole. Smagorinsky envisioned a suite of numerical models for use in understanding mechanisms for weather and climate phenomena, and for dynamical forecasts. This pioneering vision is fundamental to numerical modelling of weather and climate today. With patient and commited leadership, solid funding, and persistent scientific and engineering efforts, the 1960s and 1970s saw Bryan, Mike Cox, and collaborators such as Bert Semtner, pioneering global ocean simulations (Bryan 1969b, Bryan et al 1975, Bryan and Lewis 1979)

Release of the ``Cox Code'' (Cox 1984) established a tradition whereby GFDL provides institutional support for the use of its ocean codes. These efforts have seeded many other ocean modelling initiatives, such as those at Southampton for studies of the Southern Ocean and global eddying simulations, as well as at the Hadley Centre in the context of global climate modelling. The development of MOM1 (Pacanowski et al 1991) furthered this influence by establishing the starting point for efforts at Los Alamos, Paris, Australia, NCAR, and elsewhere. It is difficult to garner robust statistics for free software. Nonetheless, the most recent release of MOM (version 4) has more than 500 registered users since early 2004, with users coming from dozens of countries, and many representing multiple collaborators. Hence, there are well over a thousand international scientists in the MOM4 community using the code for a huge variety of scientific investigations on nearly every conceivable computer platform.

Central to the success of MOM is the ease of setting up new experiments to meet the unique needs of each investigator. This ease arises from the distribution with MOM of various auxiliary codes aimed at developing the model grid, topography, initial conditions, and boundary conditions. MOM is also packaged with the GFDL Flexible Modeling Framework (FMS). Much of the engineering exercise of running ocean models relies on powerful, yet often complex, computers. FMS provides parallelization primitives to facilitate MOM's efficient use on both vector and scalar machines. FMS also contains a general framework for coupling to other component models, such as atmosphere and ice models. Indeed, two of the roughly ten test cases with MOM4 are coupled ocean-ice models. Additionally, MOM comes with an ocean biogeochemistry model that manages multiple tracers in a flexible manner. For diagnostics, MOM incorporates the FMS diagnostic manager whereby a table entry allows for the addition or removal of a diagnostic field at runtime. Hundreds, if not thousands, of variables are tagged for inclusion in this table, and additional variables are trivial to include.

Support for a community of users is fundamental to GFDL's commitment to MOM. The reasons are many, but include the exposure that algorithms get from a broad scientific community. This exposure assists in uncovering code bugs, formulational inconsistencies, and physical limitations. To assist in this exposure, MOM developers have consistently held model documentation a primary aspect of each code release (Cox 1984, Pacanowsk et al 1991, Pacanowski 1995, Pacanowski and Griffies 1999, Griffies et al 2004, Griffies 2004. 2007). Such documentation aims to inform the MOM community regarding the rationale of its algorithms, thus assisting in the intelligent and critical use of the code. A key feature of a community model is the contribution of dynamical methods, subgrid scale parameterizations, and diagnostics to the main code branch. Nearly 20 years of MOM experience illustrate how community contributions greatly enhance the code integrity and breadth of applications. Finally, a scientifically useful numerical tool is far more than code. It is also a repository of experience garnered by a broad range of applications and wide user base. Without such experience, knowledge of the code's abilities and limitations is absent, and its use as a scientific tool is handicapped.

Suite Of Algorithms

The Cox Code was based on the Boussinesq primitive equations posed on a finite difference B-grid using z-coordinates in the vertical and spherical coordinates in the horizontal. It used the Bryan (1969a) rigid lid to split the fast barotropic waves from the slower motions of primary interest. This framework proved sufficient for an amazing number of insightful ocean climate model applications. However, as our scientific understanding of the ocean evolves, so does our understanding of how to simulate the ocean, with limitations of the early algorithms readily being exposed as applications broaden and simulations are compared to the growing suite of observations. This evolution of understanding and application has motivated the continual evolution of MOM throughout the 1990s and 2000s.

The most recent version of MOM is known as MOM4p1 (Griffies 2007). This code provides options for a suite of vertical coordinates, with pressure and functions of pressure suitable for non-Boussinesq dynamics, thus rendering a more accurate representation of the ocean free surface due to an explicit inclusion of steric effects. It uses a split-explicit algorithm for the barotropic and baroclinic motions, following the method originally proposed by Killworth et al (1991) and slightly modified by Griffies et al (2001) and Griffies (2004). This approach allows MOM to explicitly represent tides; employ a realistic hydrological cycle, rather than parameterize its effects with unphysical salt fluxes (Huang 1993); to use realistic bottom topography without concerns for rigid lid instabilities (Killworth 1987); and to run efficiently on parallel computers without bottlenecks of global sums arising in elliptic methods (Griffies et al. 2001)

MOM4 represents the bottom topography using the partial steps of Adcroft et al. (1997) and Pacanowski and Gnanadesikan (1998). Partial steps more faithfully represent the ocean's bottom by allowing the thickness of a grid cell to be a function of horizontal and vertical position. The cell thicknesses can also be functions of time, as appropriate for non-geopotential vertical coordinates such as pressure. In the horizontal, MOM4 uses generalized orthogonal coordinates, thus allowing it to exploit a broad range of locally orthogonal grids, such as the tripolar grid of Murray (1996) now standard for GFDL ocean climate simulations (Griffies et al 2004).

Leap-frog time stepping for the inviscid dynamics, standard until MOM3, has been replaced by a staggered forward time stepping scheme (Griffies 2005, Griffies et al 2005). This method removes the leap-frog computational mode, and renders a numerically precise conservation of mass and tracer. In some configurations, it can update the ocean state using twice the time step as the leap-frog, thus halving model cost.

The goal of a tracer advection scheme is to minimize dispersion errors and false extrema, maintain strong fronts and gradients, and keep spurious levels of diffusion low. There is no perfect scheme available, with MOM4p1 providing ten schemes, each with their pros and cons. However, recent experience at GFDL has shown some compelling reason to consider the Prather (1986) scheme as a benchmark for one of the best available.

Ocean climate models have traditionally been at the coarser end of the model resolution spectrum due to the global domain and long integration time. Climate resolutions necessitate a suite of subgrid scale parameterizations. MOM4 provides a suite for mesoscale eddies (Gent et al 1995, Griffies et al 1998, Griffies 1998, Visbeck et al 1997); overflows (Beckmann and Doescher 1997, Campin and Goosse 1999); tidal mixing (Simmons et al. 2004, Lee et al. 2006); lateral friction (Griffies and Hallberg 2000, Large et al. 2001); and boundary layers (Pacanowski and Philander 1981, Large et al. 1994, Chen et al. 1994).

Recent developments with MOM4p1 have exposed the code to regional modelling applications that have prompted a revision of MOM's radiating open boundary conditions. Additionally, MOM4p1 provides a wrapper for the Generalized Ocean Turbulence Model (Unlauf et al. 2005), thus facilitating the use of a wide class of turbulence closures commonly applied to regional and coastal applications.

Ongoing Development

A key aim of future coupled climate modelling at GFDL is to produce ensembles of centennial-scale simulations with a mesoscale eddying ocean using GFDL's computer resources. For this purpose, we are prototyping a 1/4 degree configuration with 50 levels. This model runs on 800 SGI Altix processors with a turnaround of roughly 100 simulated years per calendar month.

Figure 1 (page 13) shows the zonal velocity at 400m from a preliminary simulation. Space does not allow for us to compare with other simulations. Nonetheless, we note that the simulation quality is comparable to that achieved at finer resolutions, such as that described in Richards et al. (2007). We conjecture that such quality arises from the generally small lateral friction available with the Smagorinsky biharmonic scheme (Griffies and Hallberg 2000), along with the strong tracer gradients maintained with Prather (1986) advection.

In addition to MOM development, GFDL ocean model developers have focused on merging features available in three ocean models: the Hallberg Isopycnal Model, the MITgcm, and MOM. This effort aims to remedy problems inherent in each model, to more rigorously test methods and parameterizations, and to optimize human resources. The resulting unified code is expected to mature during the upcoming years into a generalized vertical coordinate model with both regional and global applications.

Dedication

Throughout the history of ocean model development at GFDL, Peter Killworth has been an active participant in the community of users and developers. We sincerely thank Peter for his years of tireless service, through insightful model applications and analyses, novel algorithm designs, and super-human efforts as editor of the journal Ocean Modelling.

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A series of quasi-global eddy-resolving ocean simulations

Sasaki, H[1], B Taguchi[1], M Nonaka[2], Y Masumoto[2, 3]
[1]Earth Simulator Center, Japan Agency for Marine-Earth Science and Technology, Yokohama, Kanagawa, Japan. [2]Frontier Research Center for Global Change, Japan Agency for Marine-Earth Science and Technology, Yokohama, Kanagawa, Japan.
[3]Graduate School of Science, University of Tokyo, Tokyo, Japan.
Corresponding author: sasaki@jamstec.go.jp

Introduction

Rapid increase of computer power and significant improvement of ocean general circulation models (OGCMs) with advanced parameterizations enable us to perform long-term simulations with global high-resolution OGCMs, which represent well not only the global circulation but also pathways of narrow strong currents such as western boundary currents, frontal structures, and small scale phenomena including mesoscale eddies. The recent advent of massive parallel computer systems, including the Earth Simulator (ES) with 40 Tflops peak performance established in 2002, has opened an era of global eddy-resolving ocean simulations. We have performed a series of quasi-global simulations on the ES with a horizontal resolution of 0.1° (see below). The simulations display oceanic mean fields and variability with rich fine-scale structures, which are comparable to available observations, and intriguing results are emerging from the realistically simulated oceanic fields. The present article introduces a few examples to illustrate the great opportunity the high-resolution ocean simulations can offer to advance our understanding of ocean circulation and its variability.

Model and simulation description

OFES (OGCM for the ES) is an OGCM parallelized and highly optimized for the ES, based on MOM3 (Pacanowski and Griffies, 1999). The horizontal resolution of our quasi-global eddy-resolving model, extending from 75°S to 75°N, is 0.1° and the number of vertical levels is 54. As our first attempt, a 50-year spin-up simulation was conducted forced by monthly climatological NCEP/NCAR reanalysis fields (Masumoto et al., 2004). Surface heat fluxes are calculated using bulk formulae, and the surface salinity flux is derived from reanalysis precipitation and estimated evaporation with an additional term restoring to the monthly climatology. Following this spin-up simulation, we have performed a hindcast simulation forced by daily NCEP/NCAR reanalysis fields for the period from 1950 to 2006 (NCEP hindcast simulation, Sasaki et al., 2007). Furthermore, an additional hindcast simulation driven by the QuikSCAT satellite wind stress, provided from the J-OFURO dataset (Kutsuwada, 1998; Kubota et al., 2002), has been performed (QSCAT hindcast simulation, Sasaki et al., 2006).

50-year spin-up simulation with monthly climatological forcing

Figure 1 (page 6) shows a snapshot of the simulated surface current in the spin-up simulation. Narrow strong currents including western boundary currents and equatorial current systems are well represented, and small scale features such as mesoscale eddies can be identified not only around the strong currents but also in interior basins. Flows through narrow passages near the marginal seas including the Indonesian archipelago, sharp frontal structures accompanying narrow currents in the Kuroshio Extension regions and the Antarctic Circumpolar Current, and separations of western boundary currents are among many examples realistically represented in the spin-up simulation. Variation of the simulated sea surface height (SSH) is also comparable to satellite observation (Masumoto et al., 2004). In the mean fields, coherent vertical structures of alternating zonal jets in the world ocean are confirmed by the OFES results, and the coupling between the jets and mesoscale eddies is implied (Maximenko et al., 2005). These successful representations in the spin-up simulation encourage us to proceed to the subsequent hindcast simulation. It is noted that the spin-up simulation has been extended up to 98-years long, incorporating chlorofluorocarbon tracers (Sasai et al., 2004).

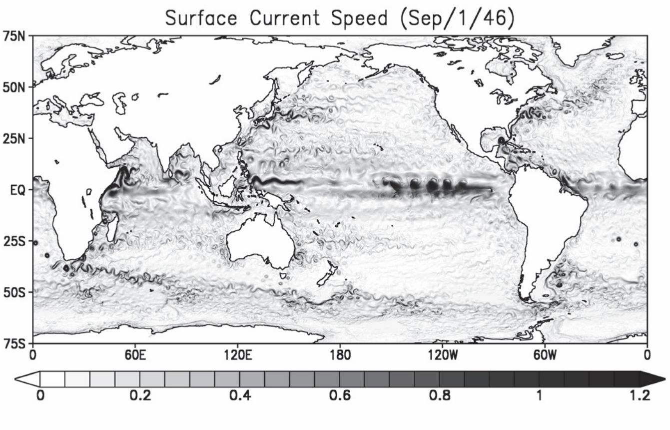

Figure 1. Snapshot of simulated surface current speed (m sec-1) based on the OFES spin-up simulation

Multi-decadal hindcast simulation with NCEP reanalysis forcing

The NCEP hindcast simulation provides a long-term dataset useful to study intraseasonal to decadal variations in realistic oceanic fields. The simulated fields capture many observed features of large-scale oceanic variations on interannual to decadal time-scale such as El Niño, Indian Ocean Dipole events, Pacific Decadal Oscillation (PDO), and Pan-Atlantic Decadal Oscillation, as well as intraseasonal variations in the equatorial Pacific and Indian Oceans (Sasaki et al., 2007). Furthermore, the multi-decadal integration of the eddy-resolving model provides an unprecedented opportunity to study the low-frequency variability of narrow oceanic jets.

A remarkable example, in this regard, is a series of studies of decadal variation of the Kuroshio Extension (KE) front, the front associated with a swift eastward current formed after the Kuroshio separates from the Japanese coast, which has recently been recognized as an important contributor to the PDO (e.g. Schneider and Cornuelle, 2005, Qiu et al., 2007). Analyzing the OFES hindcast output, Nonaka et al. (2006) demonstrated that the observed basin-wide cooling during the early 1980s in the North Pacific (Figure 2a) was accompanied by the southward shift and intensification of the two separate oceanic fronts: the Kuroshio Extension (KE) and the subarctic/Oyashio extension fronts. They attributed the subsurface cooling along the former front and the mixed layer cooling along the latter (Figure 2b) to the southward migration of the fronts, as the associated heat flux anomalies act to damp, rather than force, the temperature anomalies (reduced heat release into the atmosphere), indicating that sea surface temperature (SST) anomalies induced by the ocean feedback to the overlying atmosphere (Tanimoto et al., 2003).

Mechanisms that cause such migration of the oceanic fronts have not been fully explored due partly to their highly chaotic, nonlinear characteristics. An EOF analysis shows that wind-forced Rossby waves explain the variation in the jet over time but predict too broad a latitudinal structure (Taguchi et al., 2007). A further analysis with meridional scale separation suggests that the large-scale component of the decadal SSH anomalies in the OFES hindcast is well reproduced by the linear baroclinic Rossby wave adjustment theory (Figure 3a and b, page 13), but a much narrower structure of the KE variability results from the internal dynamics of the jet and recirculations (Figure 3c, page 13). Interestingly the large-scale and the frontal/recirculation variability exhibit nearly identical time series, which suggests that the wind-forced Rossby waves act as pacemaker regulating the intrinsic variability of the front (Taguchi et al., 2007).

Supplementary hindcast simulation with QuickSCAT wind stress forcing

In the QuickSCAT hindcast simulation, oceanic responses to the wind field including small scale features like the orographic wind in the lee of islands and near land boundaries are simulated well (Sasaki et al., 2006). For example, two branches of the South Equatorial Current in association with zonal band-like structures of the wind curl to the west of Galapagos Islands are realistically reproduced in OFES. Another example is the far-reaching Hawaiian Lee Countercurrent (HLCC) westward and in the lee of the Hawaiian Islands (Figure 4, page 13), for which two-way air-sea interactions are suggested to be important (Sasaki and Nonaka, 2006). In such interactions, the HLCC is further driven by the wind-stress curl induced by a warm SST band along the current, following the initial formation of the current at the Hawaiian Islands. This study demonstrates usefulness of the QuickSCAT simulation to investigate the impact of the small scale wind stress upon the ocean, which would never be possible without the fruitful combination of an eddy-resolving OGCM and satellite-observed high resolution wind forcing.

Summary and Discussion

A series of OFES simulations have been performed on the ES. The successful simulations provide us good opportunities to investigate not only mean fields but also variations with various temporal and spatial scales in the realistic simulated oceanic field including mesoscale eddies, narrow strong currents, and frontal structures, as briefly introduced in this article.

We have been extending the hindcast simulations up to date. Comparison of the OFES results to recent observational data from satellite and Argo profiling floats, for example, would provide us new insights about unsolved mechanisms responsible for ocean circulations and their variability. To share with the wider research community the treasure chest from OFES, we have started opening the outputs of the spin-up simulation, as a first step (http://www2.es.jamstec.go.jp/ofes/

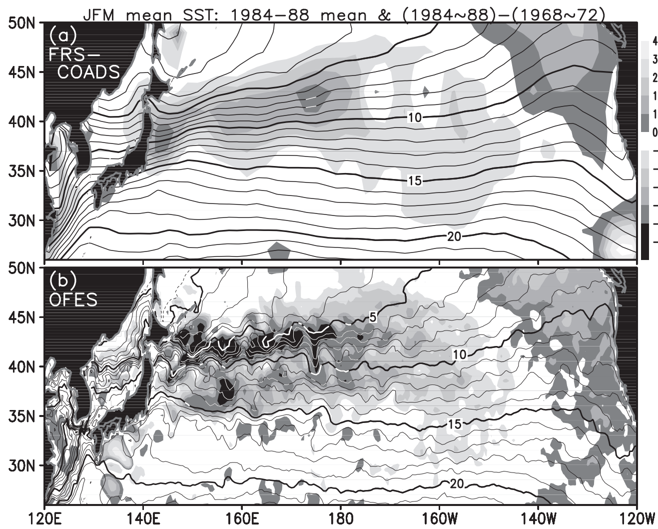

Figure 2. Wintertime (January-March) mean SST fields over the North Pacific based on (a) the observation (Frontier Research system Comprehensive Ocean and Atmosphere Data Set) and (b) the OFES simulation. Contours indicate the five winter mean for 1984-88 (every 1°C), and shade indicates the difference of that mean field from another five-winter mean for 1968-72, as indicated to the right of the top panel.

eng/). We will also open a portion of outputs from the hindcast simulation in the near future.

However, there exist some issues in the results of OFES to be solved in the near future. For example, occasional meandering of the Kuroshio south of Japan and the northwestward extent of the North Atlantic current are still unrealistic. To overcome these problems, we are trying to incorporate different parameterization schemes as well as a sea-ice model in OFES (Komori et al., 2005). Inertial mixing, tidal mixing, and non-hydrostacic processes, in addition, should be included into the future version of the high-resolution/ultra high-resolution model.

Together with the accompanying high-resolution atmospheric general circulation model (Ohfuchi et al., 2004) and the sea-ice model, a high-resolution ocean-atmosphere coupled simulation (Komori et al., 2007) is now executable on the ES, which is expected to improve predictability for high-impact phenomena with an assimilation system. Furthermore, an ocean biological model has been incorporated into OFES (Sasai et al., 2006) and will also be implemented in the coupled model in order to study predictability of marine ecosystem variability influenced by physical fields. More detailed analysis of these high-resolution models will lead us to the frontier of climate researche.

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Eddy-permitting Ocean Circulation Hindcasts Of Past Decades

The DRAKKAR Group: Barnier B., Brodeau L., Le Sommer J., Molines J.-M, Penduff T., LEGI-CNRS, Grenoble, France. Theetten S., Treguier A.-M., LPO, Brest, France. Madec G., LOCEAN, Paris, France. Biastoch A., Böning C., Dengg J., IFM-GEOMAR, Kiel, Germany. Gulev S., SIO-RAS, Moscow, Russia. Bourdallé Badie R., Chanut J., Garric G., MERCA-TOR-Océan, Toulouse, France. Alderson S., Coward A., de Cuevas B., New A., NOC, Southampton, UK. Haines K., Smith G., ESSC, Reading, UK. Drijfhout S., Hazeleger W., Severijns C., KNMI, De Bilt, The Netherlands. Myers P., DEAS, Edmonton, Canada.
Corresponding author: Bernard.Barnier@hmg.inpg.fr

1. Introduction

Research conducted by the DRAKKAR consortium is motivated by open questions related to the variability of the ocean circulation and water mass properties during past decades, and their effects on climate through the transport of heat. Of primary concern is the circulation and the daily-to-decadal variability in the North Atlantic Ocean, as driven by the atmospheric forcing, by interactions between processes of different scales, by exchanges between basins and regional circulation features of the North Atlantic (including the Nordic Seas), and by the influence of the world ocean circulation (including the Arctic). DRAKKAR carries out these investigations using a hierarchy of high resolution model configurations based on the NEMO system (Madec, 2007). Simulation outputs are carefully evaluated by comparison with collocated existing observations (Penduff et al., this issue).

The DRAKKAR consortium was created to take up the challenges of developing realistic global eddy-resolving/permitting ocean/sea-ice models, and of building an ensemble of high resolution model hindcasts representing the ocean circulation from the 1960s to present. The Consortium favours an integration of the complementary expertise from every member of the group; the coordination of a simulation program that builds a consistent ensemble of 50 year long hindcasts; and an increase of available manpower and computer resources.

2. DRAKKAR hierarchy of models

A hierarchy of embedded model configurations of different grid resolution (from coarse to eddy-resolving) has been constructed to make possible realistic, long term (several decades) simulations of the ocean/sea-ice circulation and variability at regional and global scale, and to perform sensitivity studies investigating key dynamical processes (requiring especially high resolution) and their impact at larger scales. The DRAKKAR model configurations are used by the participating research teams to address their scientific objectives. All configurations are based on the NEMO Ocean/Sea-Ice GCM numerical code and use the quasi-isotropic global ORCA grid (Madec, 2007).

2.1. Global ORCAii configurations

Global DRAKKAR configurations span resolutions of 2° (ORCA2), 1° (ORCA1), 1/2° (ORCA05) and 1/4° (ORCA025, Fig. 1 page 14).

The targeted configuration for the ensemble of hindcasts is the eddy permitting ORCA025, extensively described in Barnier et al. (2006). Such eddy-permitting models are still worth exploring and enhancing, since they will be the target resolution of the next generation of climate models. The ORCA grid becomes finer with increasing latitude, so the effective 1/4° resolution is 27.75 km at the equator and 13.8 km at 60°S or 60°N. It is ~7 km in the center of the Weddell and Ross Seas and ~10 km in the Arctic. In the vertical, there are 46 levels with partial steps in the lowest level. Coarser resolution configurations ORCA05, ORCA1, and ORCA2 are as similar as possible to ORCA025. The AGRIF refinement package (Debreu et al., 2007) allows local grid refinements as shown in the Agulhas Retroflection region (Fig. 1, Biastoch et al., 2007).

2.2. Regional NATLii configurations

Two North Atlantic/Nordic Seas configurations have been implemented: the 1/4° eddy-permitting NATL4 configuration (extracted from ORCA025), and the 1/12° eddy-resolving NATL12 configuration (Fig. 2). Both include prognostic sea-ice, and use open boundary conditions where information provided by the global hindcast experiments can be applied. The NATL12 resolution reaches 4.6 km at 60°N.

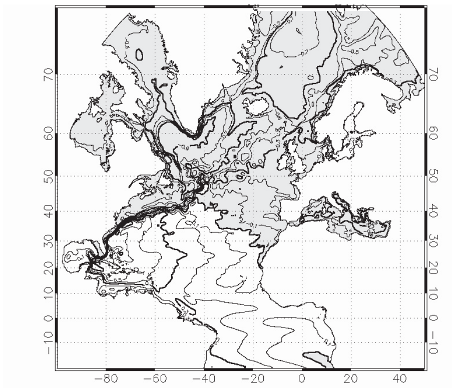

Fig. 2. The NATL12 domain (1615×1585×50 grid points with partial step) and the 2004-2006 mean SSH (in meter, contour interval of 0.1) from a hindcast started in 1998 (MERCATOR-Océan)

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3. 1958-2004 global 1/4° hindcasts carried out in 2006

A key objective of DRAKKAR is to perform long term simulations of the atmospherically driven ocean circulation and variability over the last 50 years with the ORCA025 configuration. A coordinated series of simulations were conducted in 2006 at LEGI (G70), IFM-GEOMAR (KAB0012, KAB002) and KNMI (KNM01) (Table 1), which compare the ability of the Coordinated Ocean adn sea-ice Reference Experiment (CORE) (Large & Yeager, 2004, LY04) and ERA40 atmospheric forcing data sets, and of different T,S restoring scenarios to control the strength of the Atlantic meridional overturning cell (AMOC) and global T,S drifts.

ORCA025 2006 sensitivity experiments				
Run	G70	KAB001	KAB002	KNM01
Integration period	1958-2004	1958-2004	1985-2004	1958-2004
Radiation fluxes	CORE	CORE	CORE	CORE
Turbulent fluxes	ERA40	CORE	CORE	ERA40
Precipitation	CORE*	CORE	CORE	CORE*
SSS restoring	60 days	300 days	60 days	60 days
SSS restoring under sea-ice	15 days	300 days	60 days	None
3D T,S restoring in polar areas	None	180 days	None	None
Transient Tracers	CFC_{11},C_{14b}	CFC_{11}, SF_6	CFC_{11}, SF_6	CFC_{11},C_{14b}

Table 1: Forcing parametersof the different experiments. The KNM01 experiment has not been analysed yet. KAB002 is started from KAB001 on January 1st 1985.

All experiments use the downward shortwave and longwave radiation forcing from CORE (derived from satellite ISCCP products), these variables being significantly biased in ERA40 (Brodeau et al., 2006). Turbulent fluxes are calculated using LY04 bulk formulas, input variables being wind components, air temperature and air humidity. Restoring of varying strengths to climatological sea surface salinity (SSS) is also used. In addition, for the rather uncertain precipation, two different versions were used: the original CORE fields and a modified version, CORE*, in which original CORE precipation is reduced northward of 30°N by 15-20%.

3.1. Global drifts

Fig. 3 shows the global drift in temperature and sea surface height (SSH). G70 exhibits the smallest SSH drift in 47 years, partly a consequence of the restoring to SSS but also due to an excess of freshwater (and therefore volume) in the CORE data. The comparison of KAB001 and KAB002 demonstrates that this drift is more than doubled by the 3D T,S restoring applied in polar oceans in KAB001. Drifts are very comparable in G70 and KAB002 for temperature (0.001°C/y corresponding to a surface heat flux imbalance of -0.18 Wm-2), suggesting that CORE and ERA40 turbulent fluxes have similar effects on the model drift

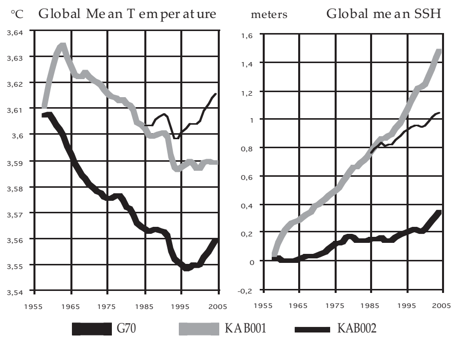

Fig. 3: Evolution of global ocean average temperature and sea level in G70, KAB001 and KAB002

3.2. Atlantic Meridional Overturning Circulation (AMOC) and deep overflows

The strongest AMOC is obtained with the ERA40 forcing and reduced northern hemisphere precipitation (G70), with a maximum of 17 Sv at 35N (Fig. 4). With the CORE forcing, an AMOC of similar structure and reasonable strength (above 14 Sv at 35N) is obtained only with the 3D restoring at polar latitudes (KAB001, not shown). Without this restoring, it collapses to under 12 Sv (KAB002, not shown). Other series of experiments with ORCA2, ORCA1 and ORCA05 confirmed that the AMOC obtained using original CORE turbulent fluxes and precipitation is significantly weaker than that obtained from ERA40 and reduced CORE precipitation in the northern hemisphere. Results from ORCA1 also highlight the importance of strong under-ice SSS relaxation in maintaining a strong AMOC.

Fig. 5 page 14 demonstrates that the weak 3D T,S restoring in polar seas (KAB001) maintains realistic dense overflows at the Nordic sills over the 47 years, whereas these waters rapidly disappear when this condition is removed in KAB002 (with a subsequent decrease of the AMOC). Meanwhile, the use of ERA40 turbulent fluxes instead of NCEP in the CORE data set, in combination with a modification (reduction) of the CORE precipation over the Arctic Ocean, allows a reasonable dense water transport at the sills to be maintained without a relaxation of this kind.

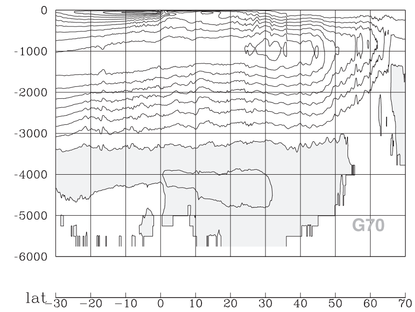

Figure 4: Mean (1990-2004) AMOC in the North Atlantic for hindcast G70. Negative vaues are shaded grey and contour interval is 2 Sv. Fig. 6:

Also the freshwater balance and its effect on the deep water formation in the Labrador Sea seem to be critical in this respect. Further sensitivity experiments are underway to identify the critical model factors governing this behaviour.

3.3. Sea-ice

ORCA025 hindcasts show a decrease of the Arctic sea-ice area since the early 1980's, as seen in satellite data. Arctic sea-ice area and concentration generally compare well with observations, in spatial patterns as well as integral values (Fig. 6, page 14). Sea-ice volume (not shown) is larger (and more realistic) in experiments using CORE turbulent fluxes (ice is too thin with ERA40). The simulation of Antarctic sea-ice is less satisfactory, with too little ice remaining in summer, and an overly large winter ice extent.

3.4. Long term variability

Hindcasts from the various integrations tend to simulate very comparable long term variabilities, i.e. an increase of the AMOC maximum (Fig. 7) in the 1980's and early 1990's and a significant decrease from the mid 1990's. However, important year-to-year differences are observed which need to be explained.

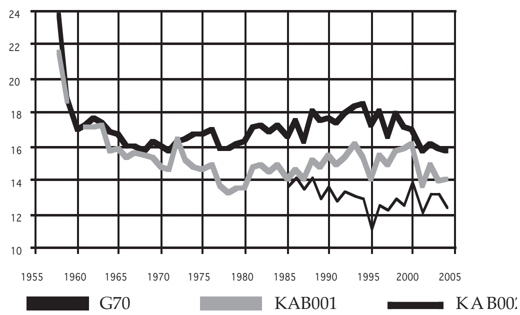

Fig. 7: Variation of the AMOC maximum in the North Atlantic in hindcasts G70, KAB001 and KAB002.

All hindcasts do a remarkable job in simulating the observed El Nino related variability (Fig. 8). However, the SST is biased warm (by a few tenths of a degree, but sometimes up to 1°C) when ERA40 the turbulent fluxes are used instead of CORE

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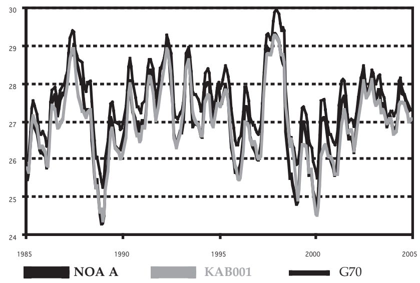

Fig. 8: Time evolution of the monthly mean ocean surface temperature (°C) in the Nino Box 3-4 in hindcasts G70, KAB001 and NOAA observations. Curve for the KAB002 run (not shown) is almost identical to KAB001.

Finally, it is obvious that applying a 3D restoring on T,S might have an impact on the simulated variability. This is illustrated in the Antarctic Circumpolar Current (ACC) transport (Fig. 9). Hindcasts without 3D restoring (G70 and KAB002) show that more than 20 years of spin-up are necessary before the ACC transport stabilises. Note that ACC transport will likely remain stronger (above 120 Sv) in KAB002 than in G70 (above 110 Sv) because of stronger winds in CORE. This spin-up phase does not exist when 3D T,S relaxation is applied at polar latitudes (beyond 50S) in KAB001. This strongly suggests that the spin-up is due to the adjustment of the mass field at high southern latitudes. The long term variability is quite different in G70 and KAB001, e.g. the latter experiment does not show the decadal oscillations typical of G70. Although weak, this relaxation tends to seriously limit the low-frequency variability.

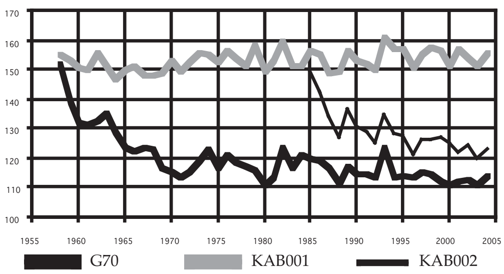

Fig. 9: Mean transport (in Sv) at Drake Passage in hindcasts G70, KAB001, and KAB002.

4. Conclusion

Series of ~50-year hindcasts (of which a small part is described here) have been carried out with the DRAKKAR hierarchy of model configurations, which has allowed improvements in model numerics, parameterizations and surface forcing. The hybrid forcing using CORE radiation fluxes and precipitation fields with ERA40 turbulent variables (wind, air temperature and air humidity), referred to as the DRAKKAR Forcing Set #3 (DFS3) is currently our best choice to obtain an AMOC of realistic strength with the ORCAii configurations. Comparison of CORE and DFS3 driven hindcasts is presently under investigation and already indicates new directions for improvements for the next forcing set (DFS4) now under construction. DRAKKAR hindcasts planned for 2007 will concern the model sensitivity to sea-ice parameters and freshwater fluxes, the objective being to completely remove any restoring to SSS. Hindcasts with the eddy-resolving configuration NATL12 will also begin. The DRAKKAR hindcast database is available upon request to research scientists outside the consortium. Additional information about DRAKKAR can be found on the project web site (www.ifremer.fr/lpo/drakkar).

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Guoxiong Wu

Congratulations to Professor Guoxiong Wu on his election as the new President of the International Association of Meteorology and Atmospheric Sciences (IAMAS). Guoxiong is a past CLIVAR SSG member and is now a member of the Joint Scientific Committee for WCRP.

Howard Cattle

Assessing The Realism Of Ocean Simulations Against Hydrography And Altimetry

Penduff, T, M Juza, and B Barnier, LEGI–CNRS, BP53, 38041 Grenoble Cedex 9, France.
Corresponding author: Thierry.Penduff@hmg.inpg.fr

Introduction

Future climate prediction systems will include ocean models at eddy-permitting to eddy-resolving resolution, i.e. ¼° on the horizontal or finer. The development and calibration of such models requires the use of more accurate numerical schemes, and the improvement of physical subgrid-scale parameterizations for the ocean interior and its boundaries, including air-sea interactions that drive the global ocean circulation and its feedbacks to the atmosphere. The DRAKKAR consortium is developing a hierarchy of basin-scale to global ocean models (Barnier et al, this issue) to simulate and study the ocean variability driven by realistic atmospheric conditions over the last 50 years without data assimilation. These oceanic hindcasts should help understand the nonlinear interactions between fine scale processes and large-scale ocean dynamics, better interpret and take advantage of satellite and in situ observations (see Penduff et al, 2006, for an overview). However, numerical simulations require quantitative model-observation mismatch evaluations to guide dynamical studies and further model improvements, and careful dynamical assessments

This paper presents an assessment method for model solutions against two complementary datasets: the ENACT-ENSEMBLES hydrographic profile database[1] which covers the period 1956-present and includes 7.4 million temperature/salinity (T/S) reports from hydrographic sections, moored arrays, floats, Argo and XBT observations; and the Ssalto/Duacs multimission Sea Level Anomaly (SLA) weekly maps from altimeter measurements[2] available since 1993. DRAKKAR models simulate the evolution since the late 1950's of T, S, velocity, sea-surface height (SSH), sea-ice characteristics, and oceanic concentrations of two tracers (CFC11, ^{14}C) released in the atmosphere over that period. These variables are stored as successive 5-day averages during the integrations. Dynamical outputs are then collocated with real observations for comparison purposes. This paper focuses on the 1958-2004 global ¼° ORCA025-G70 simulation (Barnier et al, this issue), and its 2°-resolution counterpart driven by the same surface forcing.

Data preprocessing

The collocation procedure linearly interpolates model T/S fields at the geographical locations, depths, and instants when real T/S profiles were collected. Only quality-checked (unflagged) observations are considered. Model profiles are stored in the same format as observed ones to facilitate their dissemination. Colocated profiles are then processed jointly to characterize the structure of T/S model biases in space and time. Model SSH fields are interpolated as observed SLA maps, i.e. weekly and on a 1/3x1/3° Mercator grid, from 1993 to 2004. Colocated SLA databases are obtained by masking them where and when (either real or simulated) sea-ice is present, by removing at each grid point their respective 1993-1999 mean, and by removing their global spatial average every week. Lanczos filters may then be applied to split collocated SLA fields (and thus evaluate the model skill) into distinct wavenumber-frequency ranges. We focus here on the interannual SLA variability, i.e. with timescales longer than 18 months.

Upper ocean heat and salt contents

The upper ocean, which varies and interacts with the atmosphere on a wide range of time and space scales, requires a dedicated assessment in terms of heat and salt content (HC and SC). Each colour dot in Figure A (page 15) shows, for the 50-450m layer and the period 1998-2004, a collocated bias (¼° global simulation minus Argo) of HC and SC. A cold fresh bias, whose median reaches -3°C at 250m and -0.5 psu at the surface, can be seen north of the simulated North Atlantic Current. Indeed, this current progressively tends to block over the Mid-Atlantic Ridge, like in many models at this resolution, and lets cold and fresh subpolar waters invade the region off the Grand Banks. Two other shifts are revealed in the Antarctic Circumpolar Current (ACC), which locally departs from its observed route near 45° and near 90°E. Another significant T/S bias (reaching +2°C and +0.2 psu at 200m), not fully understood yet and subject to present investigations, is revealed in the Kuroshio region. The warm and salty bias visible in the northwestern Indian Ocean is due to a spurious mixing of the Red Sea overflow; our present work on bottom boundary layer parameterizations will hopefully reduce it. The DRAKKAR group is also working on improving the surface forcing function to limit the warm and salty equatorial bias seen in the tropical Indian and Atlantic basins. Over the rest of the global ocean, collocated model and Argo profiles show smaller biases after several decades of integration.

The black and green lines in Figure B (page 15) illustrate in the Sargasso Sea how Argo is being used to assess the mixed layer annual cycle simulated at ¼° resolution, in terms of monthly heat content (MLHC), depth (MLD), and temperature (MLT). The median MLHC simulated there over 1998-2004 appears overestimated between November and April, by up to a factor of 2 in winter. The lower panels show that this substantial bias is due to a winter MLD that is twice as deep as observed, and not to a warm bias (Argo and simulated MLTs are almost identical). This approach also helps evaluate hydrographic sampling errors: our results show that, in this region, Argo accurately samples the distributions (median, percentiles) of monthly MLHC, MLD and MLT: blue lines (full model) and black lines (subsampled model) are remarkably similar. Hydrographic sampling error evaluation and model observation intercomparisons are presently being extended at global scale.

Sea level interannual variability

The 2° and ¼° DRAKKAR simulations are assessed in terms of interannual SLA variability (ISV) after colocation onto altimetric maps. Because the 2° grid is re-fined meridionally to 1/3° at low latitudes, both models simulate the ISV observed there with realistic and comparable amplitudes (Figure C page 15). At higher lati-tudes, the ISV magnitude gets more realistic at ¼° resolution, especially in the eddy-active Gulf Stream (GS), North Atlantic Current and ACC (both shifted as mentioned), Kuroshio, and Agulhas region. A space-time analysis of the ISV is shown for the GS region in Figure D (page 15). SLA fields from both simulations are projected on the 1st EOF of the observed ISV in this area. Its spatial structure $\mathbf{E}_o$ and associated

[1]http://www.mersea.eu.org/Insitu-Obs/1-Insitu-Data-ENACT.html
[2]http://www.aviso.oceanobs.com/html/donnees/welcome_uk.html

principal component $\mathbf{P}_o$ show that the GS latitude follows the NAO index in the real ocean with a 9-month lag (right panel). The ¼° model represents 19% of this mode's variance, which is modest but much greater than in the 2° model (2%). Moreover, the ¼° model captures much better the delay between the NAO forcing and the GS's response (7.8 months instead of 3.2 months at 2° resolution), yielding a better correlation with the observed ISV (0.59 instead of 0.49). Investigations of this kind are being extended to other key areas and basins of the World Ocean.

Conclusion

This quick overview of our "collocated" assessment approach has highlighted certain strengths and weaknesses of 50-year DRAKKAR simulations with respect to complementary (and recent) observations. More complete assessments are underway in other regions, depths and time ranges, and should contribute to guide model improvements. Our next multi-decadal climate-oriented simulations will be compared against the same observational databases, to precisely quantify the model sensitivities (e.g. time-mean state, various modes of variability, drifts) to thermal and mechanical surface fluxes, to resolved physical processes (e.g. mesoscale turbulence, nonlinearities, scale interactions, etc.), and to numerical choices (e.g. resolution, schemes, parameterization of non-hydrostatic, mixing or diffusive processes). These tools can also help evaluate existing or future ocean observing systems in terms of sampling errors, and strengthen the link between the observational and numerical oceanographic communities.

Ocean observations, especially prior to the recent Argo-plus-altimeter "golden age", are both rare with respect to typical scales of motion (the Rossby radius) and dispersed in time and space. On the statistical side, model-observation mismatches can always be computed, but estimating the robustness or significance of these skills may be difficult. Besides the extension of our evaluations to various regions, times-cales, periods and depth ranges, advantage should thus progressively be also taken of complementary observational datasets (e.g. satellite SSTs, current meters, tide gauges, lagrangian trajectories, etc).

Acknowledgments

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CHIME: a New Coupled Climate Model Using a Hybrid-Coordinate Ocean Component

Megann, A, A New and B Sinha, National Oceanography Centre, Southampton, UK
Corresponding author: apm@noc.soton.ac.uk

Introduction

The stability of the Atlantic overturning circulation under global climate change is of fundamental importance in predictions of the climate of northern Europe. However, time series from observational programmes (e.g. Bryden et al., 2005) are, so far, too short to resolve the current trends in the overturning, and results from numerical coupled models have to date been equivocal, with a wide spread of responses seen in the IPCC Fourth Assessment Report (2007). There are hints that the stability of the overturning in coupled models might be affected by the choice of the vertical coordinate of the ocean component: in the IPCC Third Assessment Report (Houghton et al, 2001) the ECHAM3/OPYC model, with an isopycnic ocean, showed the least reduction in MOC of all the models discussed there under realistic warming scenarios. In the Fourth Assessment Report the GISS-EH model, using HYCOM (essentially another isopycnic model) coupled to the GISS atmosphere model, was among the most stable of the nineteen models described, although a subsequent experiment with a similar model showed a significant reduction. It is important, therefore, to investigate in a rigorously controlled way how changing the vertical coordinate of the ocean model, while leaving other details unchanged, affects the stability of the overturning, and to understand what aspects of the coupled climate system in such models are so affected.

Here we introduce the Coupled Hadley-Isopycnic Model Experiment (CHIME). This model is identical to the Hadley Centre's HadCM3 coupled climate model (Gordon et al., 2000), except for its use of a hybrid-coordinate ocean model (HYCOM) instead of HadCM3's ocean model, which uses constant depth levels in the vertical. The hybrid coordinate system in HYCOM comprises constant-density layers in the ocean interior, and z-levels near the surface, and offers significant potential advantages, such as better preservation of water masses, over a purely z-level model. We describe here an experiment using CHIME with pre-industrial atmospheric greenhouse forcing, and show that there are significant differences in ocean circulation and heat transport between the two models. We would therefore expect significant differences between predictions of the future climate from the two models.

Model description

The atmosphere and ice components of CHIME are identical to those of the control run of HadCM3. The atmospheric component is HadAM3, described fully in Gordon et al. (2000), and is on a spherical grid, with cell sizes 3.75° east-west and 2.5° north-south, and uses a hybrid vertical coordinate with 19 vertical levels. The ice model (Cattle and Crossley, 1995) is a simple thermodynamic model, with ice drift defined by the ocean surface current, and partial ice coverage allowing a representation of leads.

The ocean model is the Hybrid-Coordinate Ocean Model (HYCOM; Bleck, 2002). In the interior, which in the present model configuration constitutes more than 93% of the ocean domain by volume, the vertical coordinate is essentially isopycnic over the whole annual cycle. Near the surface, the layers are constrained to have a minimum thickness and their density is allowed to vary; typically this results in z-layers in the upper 50-150 metres of the ocean. The vertical coordinate is potential density referred to a 2000 dbar pressure, and the thermobaric correction of Sun et al. (1999) is applied. South of 55°N, the ocean grid is identical to that used in HadCM3, while north of 55°N a bipolar grid, with poles at 110°W and 70°E, is used (this removes the North Pole island used in HadCM3). In addition, the model uses the KPP vertical mixing scheme (Large et al., 1994).

From Griffies et al, page 3: Ocean Modelling with MOM

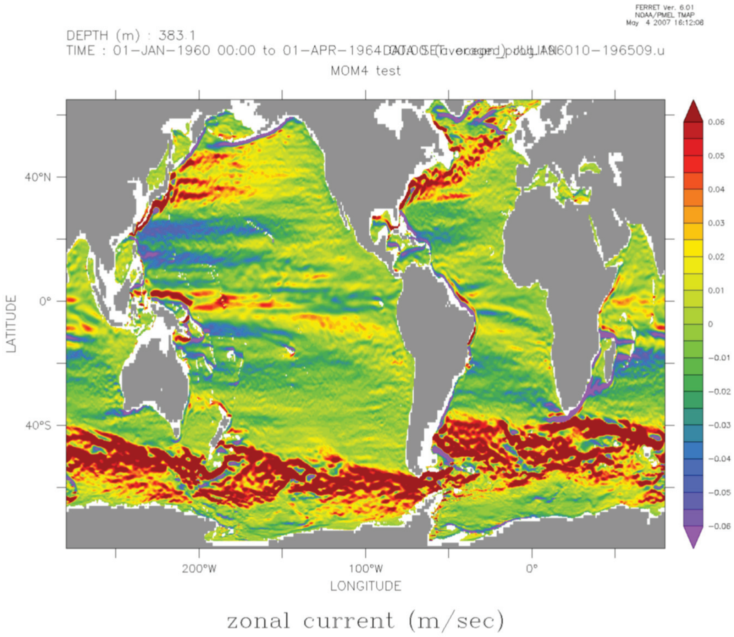

Figure 1: Five year mean zonal velocity at 400m in a global 1/4 degree MOM simulation. These currents show signs of the latitudinally alternating zonal jets described by Richards et al. (2007), which were seen in a 1/10 degree simulation as well as satellite altimetre observations

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From Saski et al (page 5): A series of quasi-global eddy-resolving ocean simulations

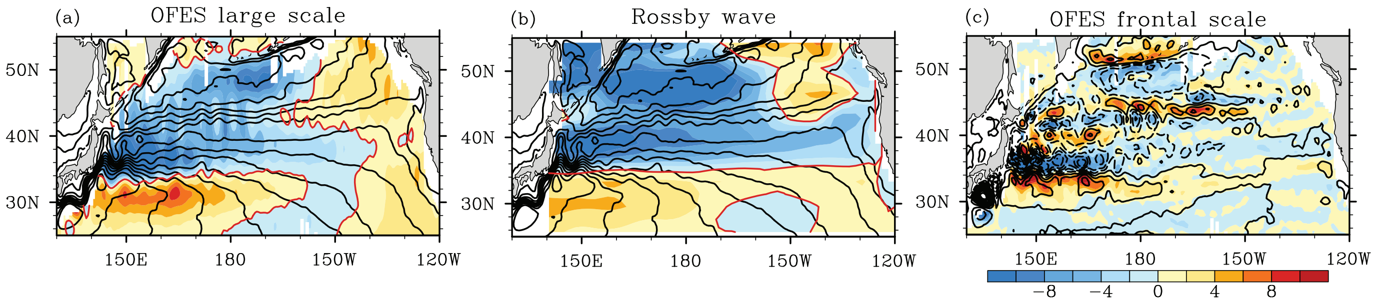


Figure 3. (a) Broad-scale component of the post (1984-1996) minus pre-shift (1968-1980) difference in OFES SSH (color shade in cm). Unfiltered OFES SSH averaged for both periods is superposed with black contours (at intervals of 10 cm). (b) Same as (a) but for SSH anomalies from the Rossby wave model (shade). (c) Same as (a) but for frontal-scale SSH (shade). Black contours designate differences in the unfiltered OFES SSH between the two periods with contour intervals of 5 cm.

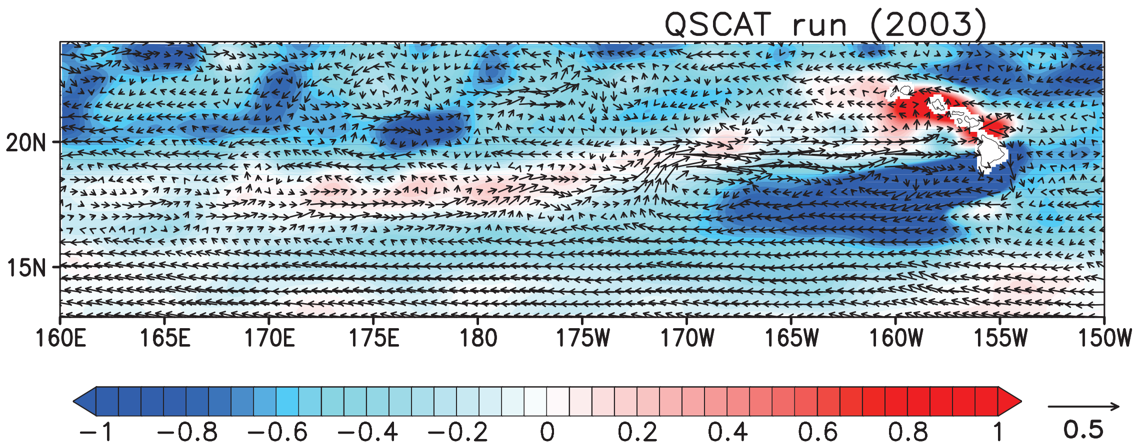


Figure. 4. Annual mean current vectors at 38 m depth (m sec^{-1}) and surface wind stress curl (color, unit: 10^{-7} N m^{-3}) in 2003 based on the OFES QSCAT simulation.

From Barnier et al, page 8: Eddy-permitting Ocean Circulation Hindcasts of Past Decades

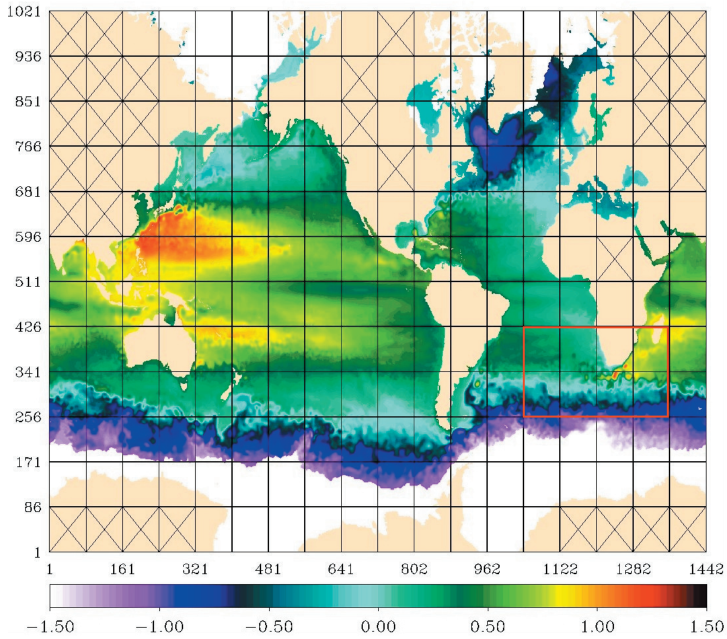
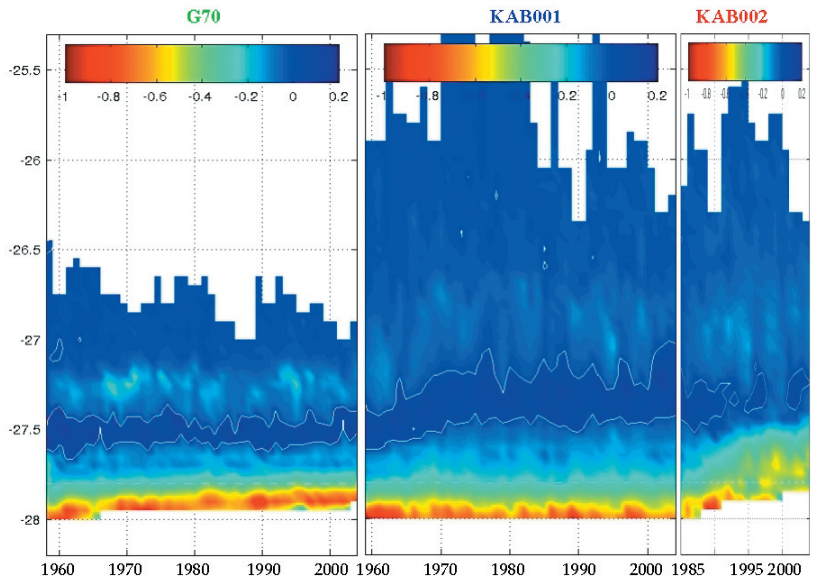


Fig. 1: ORCAii global configurations. The model domain and land-sea mask are shown for the 1/4° ORCA025 configuration (axes correspond to grid points). Colours show a SSH snapshot (in meter) on June 24, 1998 from one of the hindcast runs (G70), sea-ice cover being in white. Boxes show the domain decomposition on a large number of processors, ocean processors (not marked by a cross, 186 of those) being the only ones retained in the calculation. On vector computers a more moderate parallelization (typically up to 32 processors) is used. The red box is the region where a 2-way grid refinement at 1/10-1/12°is being implemented.

Figure 5: Evolution of the annual mean transport (in Sv) by density classes across the Denmark Strait. Negative values indicate a flow from the Nordic Seas into the Atlantic. The zero contour line is shown in white.



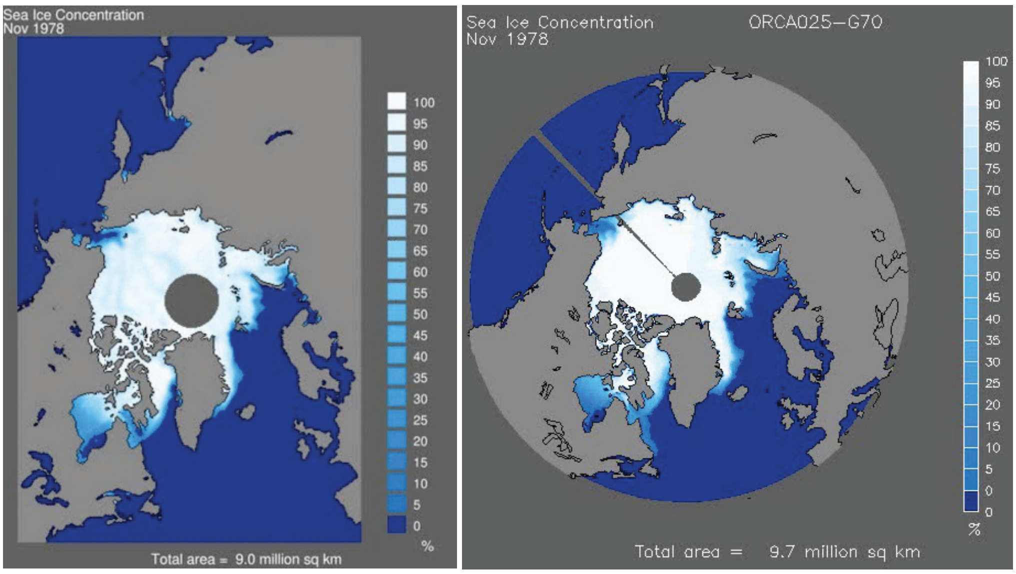


Fig. 6: Monthly mean sea-ice concentration and total area in November 1978 (left) from satellite observations (Sea Ice index, Fetterer and Knowles, 2002) and(right) from the G70 hindcast.

From Penduff et al (page 11) Assessing The Realism Of Ocean Simulations Against Hydrography And Altimetry

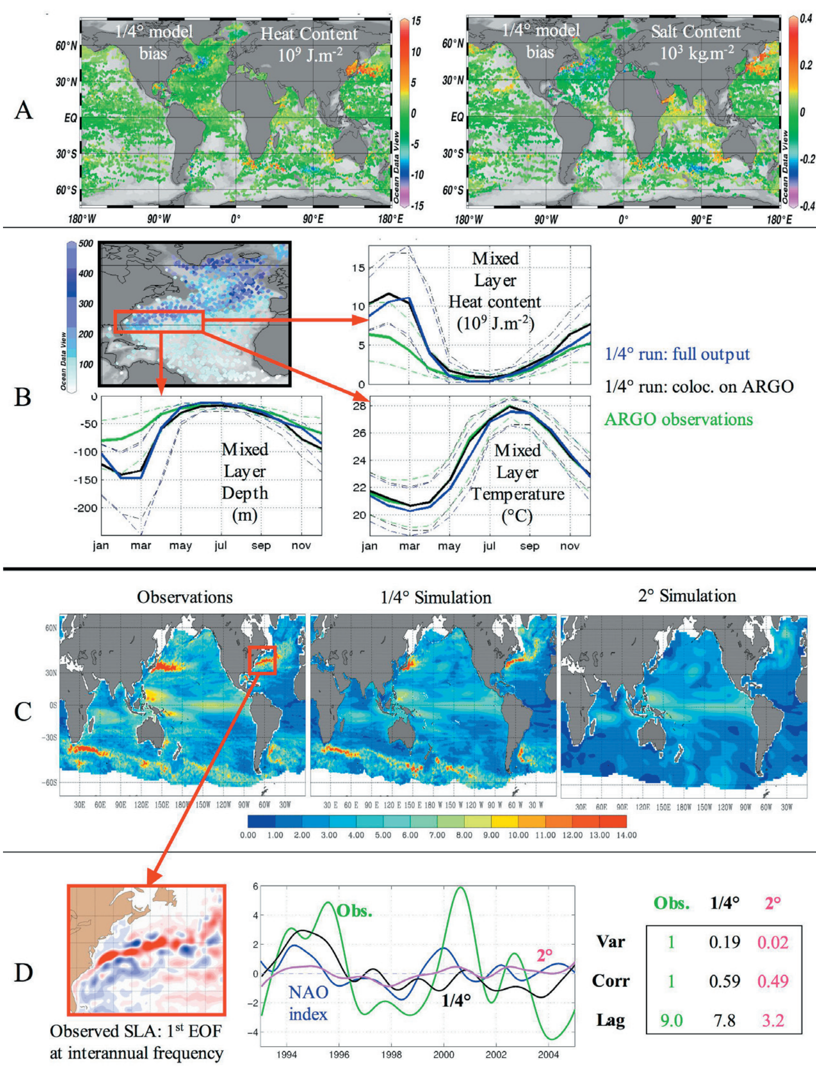


Figure A. Mixed layer heat and salt content biases from the ¼° simulation collocated with Argo profiles over 1998-2004. Each color dot quantifies a synoptic model bias.

Figure B. Top left: Local mixed layer depth (MLD) estimates from Argo in February (1998-2004). The MLD corresponds to a 0.2°C temperature change (Montegut et al, 2004). Other panels: Monthly mixed layer statistics (heat content in 10^9 J/m^2, depth in m, temperature in °C) over 1998-2004 in the Sargasso Sea from the full ¼° simulation (blue), Argo (green), and the model collocated with Argo (black). Medians (thick lines) and 17%/83% per-centiles (dashed) characterize monthly distributions.

Figure C. 1993-2004 standard deviations (cm) of observed and simulated low-frequency (LF) SLAs.

Figure D. Left: normalized 1st EOF $\mathbf{E_o(x,y)}$ *of the observed LF SLA in the Gulf Stream region. Center: Principal component* $\mathbf{P_o(t)}$ *in cm associated with* $\mathbf{E_o}$ *(green), low-passed filtered NAO index N(t) (blue), projection of simulated SLAs on* $\mathbf{E_o}$ ($\mathbf{P_{1/4}(t)}$ *in black for the ¼° model,* $\mathbf{P_2(t)}$ *in magenta for the 2° model). Right panel: variances of* $\mathbf{P_o}$, $\mathbf{P_{1/4}}$, *and* $\mathbf{P_2}$ *scaled by the variance of* $\mathbf{P_o}$ *(line 1). Correlation of* $\mathbf{P_o}$, $\mathbf{P_{1/4}}$ *and* $\mathbf{P_2}$ *with* $\mathbf{P_o}$ *(line 2). Lag between N and* $\mathbf{P_o}$, $\mathbf{P_{1/4}}$, $\mathbf{P_2}$ *in months (line 3).*

from Megann et al page 12: CHIME: a New Coupled Climate Model Using a Hybrid-Coordinate Ocean Component

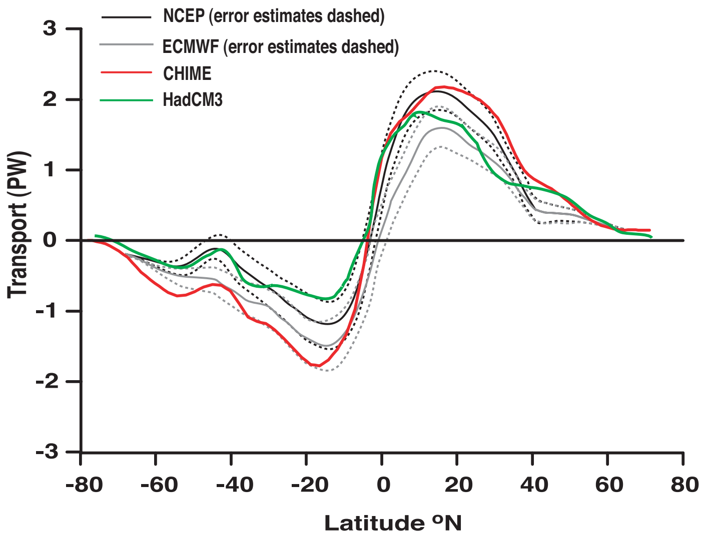


Figure 1: Global meridional oceanic heat transport in CHIME (red curve) and HadCM3 (green curve) in years 80-120. The other curves are from the estimates of Trenberth & Caron (2001) from the NCEP (black) and ECMWF climatologies (grey) with the errors shown dashed.

From Stark at al, page 18 The impact of the simulation of the Agulhas retroflection on the evolution of the coupled climate model HadGEM1

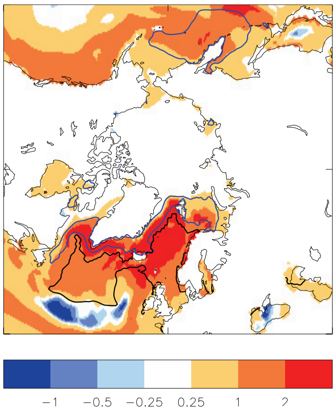


Figure 1: Change in SST in the Northern hemisphere between the average of years 346-355 and years 11-20. The region where sea ice concentration has decreased by more than 10% is shown within the blue contour. The outcrop region for the 27.2 isopycnal (defined as where the isopycnal is less than 50m deep in ice free ocean) is shown within the black contour. Note non-linear scale.

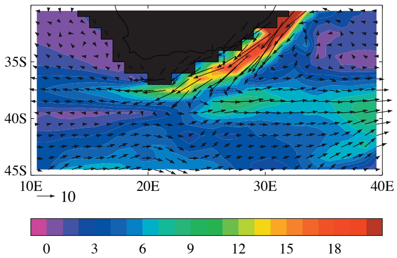


Figure 3: HadGEM1 velocity field on the 27.2 isopycnal (the core of the model AAIW) for years 1-10.

From Piggot et al, page 21: Multi-scale ocean modelling with adapting unstructured grids

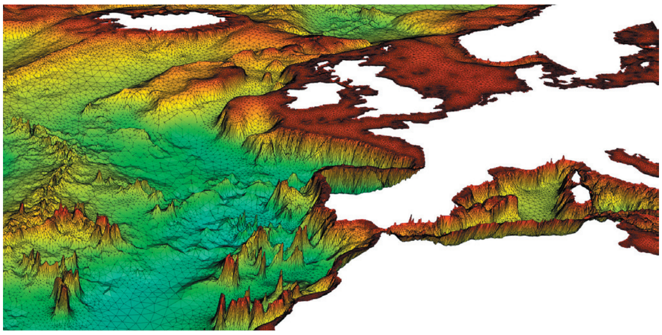


Figure 1: Section of unstructured mesh generated for the North Atlantic. The representation of the bathymetry and coastlines has been optimised using Terreno (Gorman et al., 2006). Regions of high curvature, such as the mid-Atlantic ridge and Celtic shelf break make use of increased anisotropic resolution.

From Tsujino et al, Page 19: Improved representation of currents and water masses in the upper layer of the North Pacific Ocean in eddy-resolving OGCM

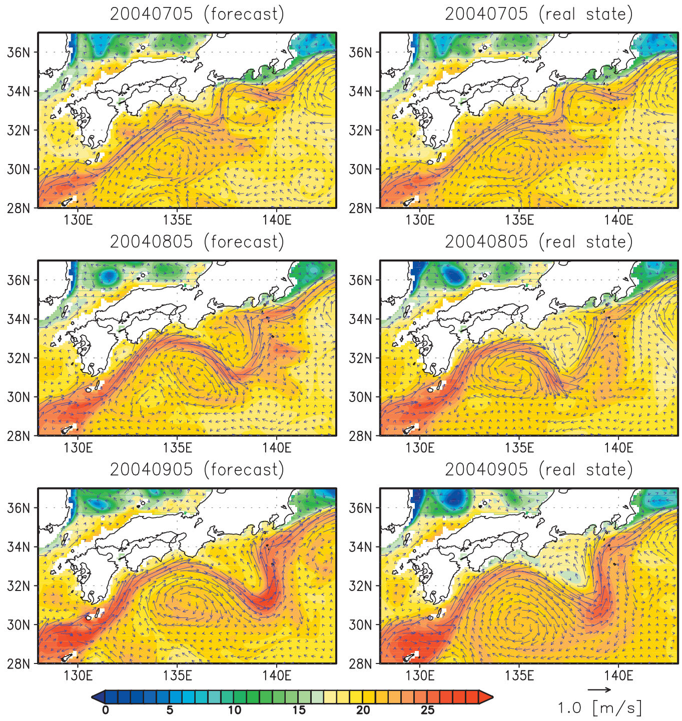


Figure 4: A forecast experiment of the oceanic state around Japan. Left panels: forecast. Right panels: real state estimated by data assimilation. Shade and vector is temperature and velocity at 100 m depth, respectively. The prediction begins on 1 July 2004 with an initial condition obtained from the data assimilation. The evolution of the oceanic state is shown by the interval of 30 days. This case is the development of the Kuroshio large meander, which is the sole large meander event since 1990.

From Sen Gupta et al, page 23: Atmosphere – Ocean – Atmosphere coupling of the Southern Annular Mode

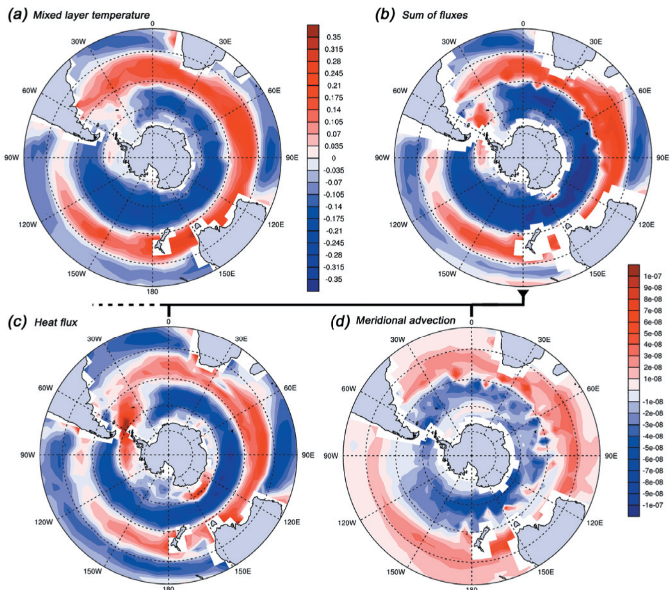


Figure. 2 Heat budget analysis: $\frac{\partial T^M}{\partial t} \approx \frac{Q_N}{\rho_o C_p (MLD)} - u\frac{\partial T^M}{\partial x} - v\frac{\partial T^M}{\partial y} - u\frac{\partial T}{\partial z}\Big|_{MLD}$ *where T^M is the mixed layer temperature, Q_N is the net surface heat flux, C_p is the specific heat capacity of seawater, ρ_0 is a reference density and MLD is the monthly mean mixed layer depth. Panels show regressions on SAM index of (a) mixed layer temperature (^oC); (b) sum of mixed layer heat budget terms ($^oCs^{-1}$); (c) net surface heat flux term ($^oCs^{-1}$) and (d) meridional heat advection term ($^oCs^{-1}$). Colour scaling is identical in panels (b)-(d)*

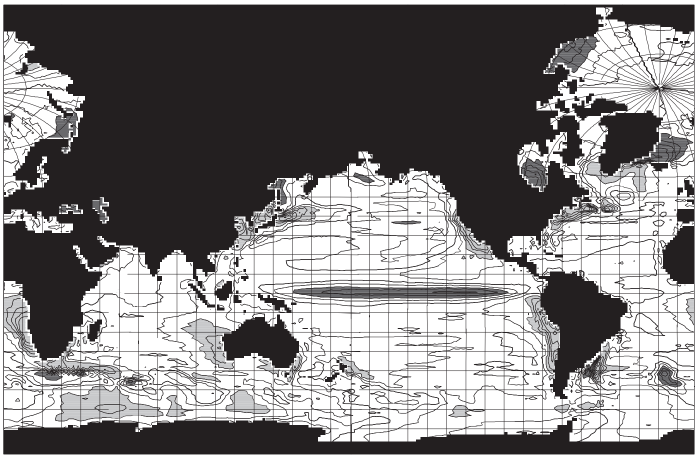


Figure 2: Ocean surface temperature errors in CHIME from the NOCS (Josey et al., 1998) climatology, averaged over the first decade of the model run. Dark grey shading indicates cold errors of more than 2°C, while light grey shading denotes warm errors greater than 2°C; the zero contour is in bold.

The ocean and atmosphere exchange fields via the OASIS coupler, and interpolation of the fields between atmosphere and ocean grids is carried out by the ocean model. A significant difference from HadCM3 is that the coastlines of the ocean model are on the finer ocean grid, rather than on the atmosphere grid, so a coastal tiling scheme is employed to correctly allocate fluxes between sea, land and atmosphere components.

Results

CHIME was run with fixed pre-industrial atmospheric CO_2 for 120 years, and here we compare this model with the same period of the HadCM3 control experiment. The mean meridional overturning in the North Atlantic is similar both spatially and in magnitude to that of HadCM3. The ocean northward heat transports in CHIME (Figure 1 page 15) are generally within the bounds of the estimates of Trenberth and Caron (2001), as are those in HadCM3. However it is clear that at most latitudes the heat transport in CHIME lies towards the upper limits of the climatological estimates, while that in HadCM3 consistently lies towards the lower limits. The differences in heat transport between the models in the Northern Hemisphere are consistent with the observation that the volume transport in the western boundary currents (the Kuroshio and the Gulf Stream) in CHIME are generally 20-30% larger than in HadCM3, although the reasons for this are at present unknown.

Gordon et al. (2000) showed that the global mean surface temperature error in HadCM3 is small (less than 0.2°C) and very stable over a time scale of several centuries. In that model there is a cold bias of up to 4°C over the North Pacific, as well as a cold error along the equatorial Pacific; these are balanced by warm errors in the Southern Ocean and along the eastern boundaries of the tropical Atlantic and Pacific. The global mean SST error in the first decade of CHIME (Figure 2) is similar to that in HadCM3, but with the North Pacific cold bias replaced by a warm error of 3-4°C. The respective surface errors in the North Pacific in both models appear to be primarily related to a meridional shift in the path of the North Pacific Current, which lies about 3° north of the observed path in CHIME, but about 3° too far south in HadCM3. In CHIME the subtropical gyres in both the North Atlantic and North Pacific warm gradually, as a result of the high northward heat transport in the boundary currents, leading to a global mean SST error of about 1.5°C by 120 years.

CHIME is now participating in the UK NERC RAPID climate model intercomparison project, and experiments with increasing greenhouse forcing and North Atlantic freshwater hosing will be carried out. This will allow an investigation of the response of the MOC to global warming in CHIME, and in particular an assessment of the relationship between the MOC and the north-south steric height gradient, and comparisons with such a relationship derived from HadCM3 (Thorpe et al. 2001).

Acknowledgments

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The impact of the simulation of the Agulhas retroflection on the evolution of the coupled climate model HadGEM1

Stark, S, H. T. Banks, I. D. Culverwell and A. B. Keen, Met Office, Hadley Centre, Fitzroy Road, Exeter EX1 3PB, UK
Corresponding author: Sheila.Stark@metoffice.gov.uk

Coupled climate models are commonly used to make predictions of changes in the climate system. By the time of the third assessment report of the IPCC (2001), coupled models had began to be developed without flux adjustment and with a reasonably stable climate. With the use of flux adjustment techniques, ocean water masses are less likely to drift away from climatological values as the surface properties are constrained to be close to observed values. It is therefore important to quantify the response when flux adjustments are not used, as the drifts have the potential to be significantly larger.

HadGEM1 (Johns et al., 2006) is a coupled climate model run without flux adjustment. Over the first 600 years of the integration the net radiative flux at the top of the atmosphere is initially negative (outgoing) but within a few years adjusts towards a positive (incoming) flux. The net incoming flux leads to net warming of the climate system. The flux transitions from 0.31 W/m^2 in years 0-200, 0.20 W/m^2 in years 200-400 and reaches a quasi-equilibrium of 0.12 W/m^2 in years 400-600. The multi-century timescale suggests that the ocean plays a dominant role in this adjustment.

The long timescale reduction in the radiative flux at the top of the atmosphere can be explained by an increase in outgoing longwave radiation partly offset by a decrease in outgoing shortwave radiation. The increase in outgoing longwave radiation is forced by an increase in global mean SST of 0.2^{o}C between years 200 and 350 while the decrease in shortwave radiation is forced largely by a 10% reduction in sea ice area. The increase in sea surface temperature is confined to the North Atlantic subpolar gyre and the Greenland Sea and can be explained by warm, salty water on the outcrop of the 27.2 isopycnal and the associated retreat of the sea ice (figure 1 page16).

The 27.2 isopycnal is where Antarctic Intermediate Water (AAIW) is found and the warm anomaly on this isopycnal can be traced back to the South Atlantic where the AAIW salinity minimum erodes. The erosion of AAIW is first seen as a saline anomaly in the fifth month of the experiment. This anomaly grows rapidly and spreads, filling the subtropical gyre and eroding the Atlantic salinity minimum. Subsequent salting of the intermediate depth Atlantic is rapid; figure 2 shows that by year 100 the salinity minimum has retreated to 28°S.

The flow off South Africa is dominated by the Agulhas Current and its retroflection. The Agulhas Current flows westward along the southern coast of Africa with the majority of the flow retroflecting back into the Indian Ocean as the Agulhas Return Current. The strength of the Agulhas current is well simulated by HadGEM1. Bryden et al. (2005) cite a mean transport of 69.7 Sv at 31°S in the Indian Ocean; at the same latitude the mean flow in the first decade of HadGEM1 is 68.8Sv. However, in HadGEM1 there is little retroflection with the majority of the flow continuing westwards into the Atlantic basin (figure 3, page 16). At 25°E the Agulhas transport in the model is 50.4 Sv, 40% of which occurs in the AAIW layer. At 20^{o}E where retroflection should occur (Dijkstra and de Ruijter, 2001), the model exhibits a westward transport of 34.0Sv.

At the resolution of HadGEM1 (1 degree in the Agulhas region) a realistic simulation of the Agulhas current and its retroflection is difficult to achieve. Two sets of sensitivity experiments were carried out to see if the simulation could be improved. First, the representation of the bottom topography and continental shelf were varied to steer the flow. Second, the effect on the flow of a range of viscosity settings was explored to try and push the model into either an inertial or frictional regime. Some improvements were seen though none of the experiments exhibited a realistic circulation in the Agulhas retroflection region. Improved steering of the flow was seen in an experiment with a more realistic topography than is used in HadGEM1 but an unrealistic bathymetry is required to have a dramatic impact on Atlantic salinity. At high viscosity the Agulhas current is sufficiently choked to inhibit erosion of Atlantic AAIW but little retroflection is seen even at low viscosity (Stark and Culverwell, in preparation). In Hadley Centre models an improved simulation of the Agulhas retroflection appears only to be possible at higher (1/3°) resolution.

In conclusion, in HadGEM1 the lack of a realistic Agulhas retroflection results in a strong westward transport of saline Indian Ocean water into the Atlantic Ocean eroding the salinity minimum of Antactic Intermediate Water. The anomalous water mass source in the South Atlantic is quickly advected northwards throughout the Atlantic as also seen in the experiments of Weijer et al. (2002). When the warm, salty water outcrops in the North Atlantic, it increases SST, leads to reduction of Arctic sea ice and adjusts the top of the atmosphere radiation through changes to outgoing longwave and shortwave fluxes (Banks et al., 2007). There are also impacts on the overturning circulation in the Atlantic. These results highlight the importance of a good simulation of the Agulhas current and its retroflection in climate models.

Acknowledgments
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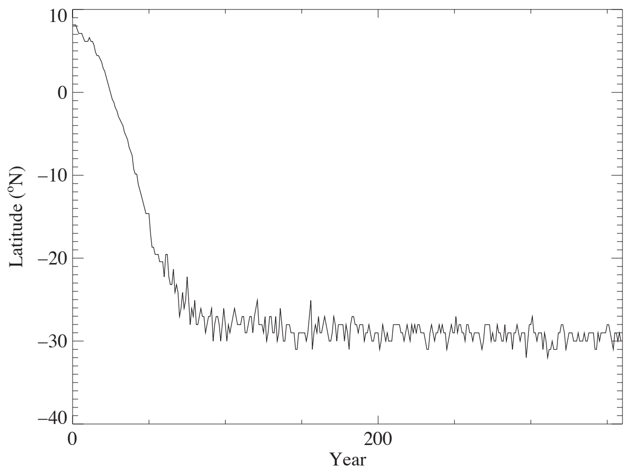

Figure 2: Timeseries of the most northerly extent of AAIW at 20^{o}W. AAIW is defined here as a salinity of 34.7psu on the 27.2 isopycnal (the core of the model AAIW).

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Improved representation of currents and water masses in the upper layer of the North Pacific Ocean in eddy-resolving OGCMs

Tsujino, H and Y Fujii, Meteorological Research Institute, Tsukuba, Ibaraki, Japan
Corresponding author: htsujino@mri-jma.go.jp

1. Introduction

Oceanic components of global coupled Atmosphere-Ocean-Land-surface models generally have a horizontal resolution of order 100 km, and effects of meso-scale eddies are parameterized. The highest horizontal resolution realized in oceanic components of global coupled Atmosphere-Ocean-Land-surface models is about 20 km (Sakamoto et al. 2005). This model explicitly generates meso-scale eddies, showing qualitative improvements to the simulated fields. Outcomes of such a model enable us to assess how global climate changes affect the marine environment around coastal areas. But we should note that a 20 km model only marginally resolves meso-scale eddies. This is why such models are called the eddy-permitting models.

Our research group develops a higher (10 km) resolution model of the North Pacific Ocean and studies mechanisms and predictability of the upper layer currents and water masses in the mid-latitude western North Pacific Ocean. This article presents some improvements in the representation achieved by increasing the horizontal resolution of the OGCM from 20 km to 10 km.

2. Model and its Validation

The Meteorological Research Institute Community Ocean Model (MRI.COM) is a MOM-type z-coordinate model. A major difference from GFDL-MOM is that coastlines are created by connecting tracer points instead of velocity points. It is designed for various purposes, for example, it is coupled with the atmospheric model of MRI and it is applied to data assimilation. Major physical and computational schemes are available, including high-order advection schemes, mixed layer models, and a sea ice model.

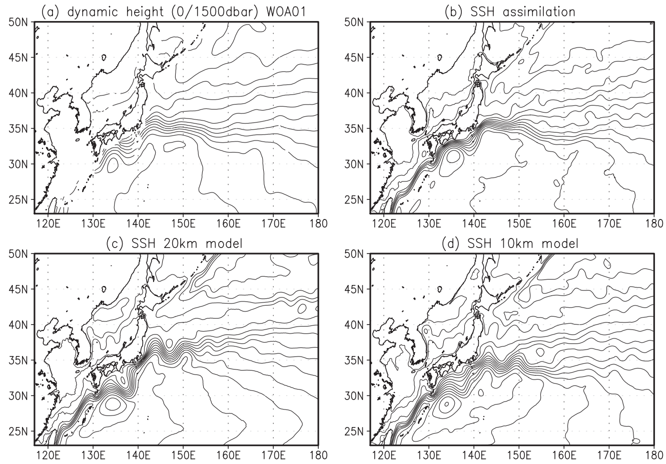

Figure1: Sea surface height (SSH) in the western North Pacific of (a) World Ocean Atlas 2001 (WOA01), (b) data assimilation, (c) 20 km model, and (d) 10 km model. Contour intervals are 10 cm. (a) dynamic topography relative to 1500 dbar. (b) average from 1993 to 2005. (c, d) average from year 51 to year 70.

domain	Pacific Ocean north of 15ºS. Temperature and Salinity are restored to *World Ocean Atlas 1998* at the southern wall, other side boundaries are closed.
resolution (20 km model)	1/4º (zonal), 1/6º (meridional). 61 levels.
resolution (10 km model)	1/12º (horizontal). 61 levels.
surface forcing	climatological atmospheric state (average from 1979 to 2004) from NCEP-DOE AMIP-II reanalysis (Kanamitsu et al. 2002) and a bulk formula of Kara et al. (2000).
horizontal viscosity	bi-harmonic Smagorinsky-like viscosity (Griffies and Hallberg 2000).
horizontal diffusion	bi-harmonic diffusion coeff. = $1\times10^8\ m^4s^{-1}$
initial state (20 km model)	*WOA98* integration: year 1 – year 70
initial state (10 km model)	end of year 20 of 20 km model integration: year 21 – year 70

Table 1: Feature of the North Pacific simulations

Two simulations, differing only in horizontal resolutions, are performed for the North Pacific Ocean circulation. Basic settings are summarized in Table 1.

For validation, we use the climatological fields of an oceanic reanalysis conducted by our research group (MOVE/MRI.COM-WNP; Usui et al. 2006a; 2006b) in addition to the World Ocean Atlas 2001 (Conkright et al. 2002). The data assimilation method is a multivariate three-dimensional variational (3DVAR) analysis scheme with vertical coupled temperature-salinity empirical orthogonal function. In-situ observations and sea surface height anomalies from satellite altimetry are assimilated into a nested-grid regional high-resolution (horizontally 10 km) model for the western North Pacific from 1993 to 2005. This is part of an assimilation and prediction system that has been developed for forecasting the marine environment around Japan.

3. Results

Figure 1 shows the climatological sea surface height, which can be regarded as the stream lines for surface geostrophic currents. The Kuroshio separates steadily from the Japan coast, and the

Kuroshio Extension and the inertial recirculation gyre south of it are formed more realistically in the 10 km model than in the 20 km model. A process study conducted by Nakano et al. (personal communication) suggests that the realistic separation and recirculation gyre are tightly interrelated and that inertial terms of the momentum equation must be large for their formation. This is attainable only in high resolution models.

Upper layer stratification in the mid-latitude frontal region is improved in the 10 km model (Figure 2). Isothermal contours are flattened in the 10 km model. We speculate that this re-stratification might be caused by the act of meso-scale eddies or the baroclinic instability that release the potential energy that the 20 km model field has.

The improved current fields result in the improved representation of water masses. We first take up the North Pacific Intermediate Water (NPIW), characterized by the salinity minimum in the intermediate layer (Figure 3). NPIW is well reproduced in the 10 km model. On the other hand, the low salinity water from the high latitude region can hardly cross the fronts between 35° - 45°N in the 20 km model. Analyses conducted by Ishikawa and Ishizaki (personal communication) suggest that the strained structures of tracer fields related to eddy activities carry the subpolar low salinity water further southward into the subtropical gyre in the 10 km model than in the 20 km model. This difference in the small scale processes is caused by the difference in dissipation. The horizontal viscosity and the numerical diffusion in our experiment are determined by the 3rd power of the horizontal grid size. These are significantly smaller in the 10 km than in the 20 km model since a factor difference in resolution results in an order difference. Thus, the higher resolution reduces dissipation of small scale processes, resulting in the increase in the southward fresh water transport by those processes.

Subtropical mode water (NPSTMW), another major water mass in the upper layer subtropical North Pacific, is created in the deep winter mixed layer south of the Kuroshio Extension (35°N) and its thermostad penetrates south-westward. Figure 2 shows that the representation of NPSTMW in the 10 km model is closer to observation than in the 20 km model. These features are due to the improved upper layer circulation associated with the well developed Kuroshio recirculation in the 10 km model (Figure 1).

With the aid of data assimilation techniques, a 10 km model is used for the forecast of the marine environment around Japan, including the large meander of the Kuroshio south of

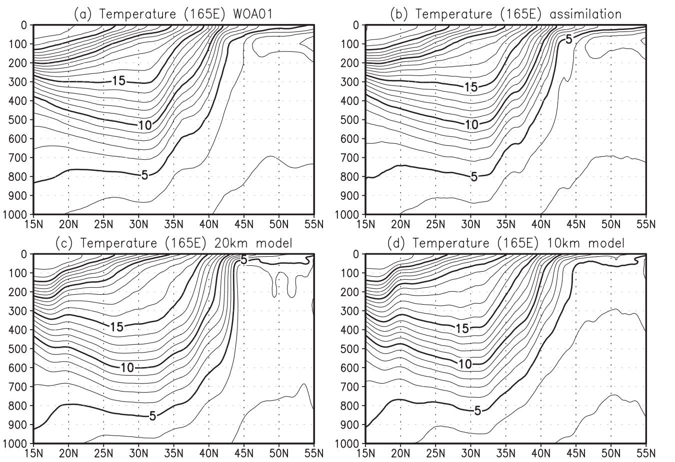

Figure 2: Same as Fig. 1 but for vertical section of temperature along 165°E. Units are in degrees Celsius (°C). Contour intervals are 1°C.

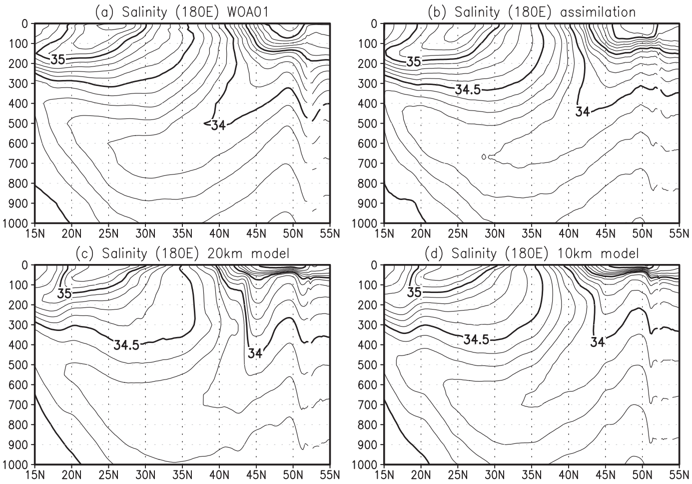

Figure 3: Same as Fig. 1 but for vertical section of salinity along 180°. Units are in practical salinity unit [psu]. Contour intervals are 0.1 [psu].

Japan. This system shows good skill in predicting the Kuroshio meander (Figure 4 page 16). The predictive limit for the sea surface height south of Japan is about 50 days. This system is planed to be implemented as the operational system of the Japan Meteorological Agency.

4. Summary

We find many improvements by increasing horizontal resolution from 20 km to 10 km. The extension and recirculation extends further eastward in the 10 km model than in the 20 km model. The improved currents lead to improved water mass distributions. The processes whose scales are smaller than the size of typical meso-scale eddies affect the formation process of water masses. Motivated by these results, we plan to further increase the horizontal resolution of basin scale models.

Findings in this study also indicate that it may be desirable for an oceanic component of a coupled Atmosphere-Ocean-Land-surface model to have a horizontal resolution higher than 10 km in the mid-latitude regions. In such a model, the mid-latitude oceanic boundary currents, fronts, and water masses shall be properly represented, which is crucial for successful modeling of marine environment and terrestrial system through air-sea-land interactions.

Finally, we note that an oceanic reanalysis serves as a reference data set for model validation. Also, we can find what is deficient in a model through the course of data assimilation experiments, which helps us improve models.

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Multi-scale ocean modelling with adapting unstructured grids

Piggott, MD[1], CC Pain[1], GJ Gorman[1], PD Killworth[2], DP Marshall[3], PA Allison[1], AP Umpleby[1], CJ Cotter[1], F Fang[1], LM Bricheno[3], LJ West[2], HL Johnson[3], DR Munday [3], DA Ham[1], H Liu[1], SC Kramer[1], TM Bond[1], Y Soufflet[2], J Shipton[3], MR Wells[1], AS Candy[1], C Bain[3], ZL Roberts[2], BT Martin[1], PE Farrell[1], AJ Mitchell[1], A Shravat[3], S Tukova[3], CRE de Oliveira[1], AJH Goddard[1].

[1]Applied Modelling and Computation Group, Dept. of Earth Science and Engineering, Imperial College London, SW7 2AZ, UK

[2]Ocean Modelling and Forecasting, National Oceanography Centre, Southampton, SO14 3ZH, UK

[3]Atmospheric, Oceanic and Planetary Physics, University of Oxford, OX1 3PU, UK

Corresponding author: m.d.piggott@imperial.ac.uk; http://amcg.ese.ic.ac.uk

Motivation

When modelling the oceans one must contend with high Reynolds number multi-scale dynamics in a highly complex domain where the effects of buoyancy and rotation dominate. These features pose significant challenges for numerical methods. Unstructured meshes represent an attractive new approach to ocean modelling where for a start the highly accurate representation of coastlines and bathymetry is possible (Figure 1 page 16). Unstructured meshes are also ideal for achieving smooth variations in resolution across a domain. Adaptive mesh methods may also be employed with the aim of altering the mesh throughout a simulation, as guided by error measures reflecting complexity in the flow and/or discretisation errors, so as to make more optimal use of limited computational resources. This optimised use of resources has applicability for both eddy-resolving simulations as well as at the coarser overall resolutions typically used in climate models where western boundary currents and overflows for example would benefit from enhanced representation.

The most appropriate use of mesh resolution in a particular simulation will of course depend upon the question being answered or the hypothesis being tested. Ideally a user should have a broad idea of which regions or physical processes should be optimised for in the simulation, and be in a position to encode this in the error measure guiding the adaptive algorithm. In some situations this could involve a degree of trial and error, perhaps exposing the fact that in a highly nonlinear system initially innocuous aspects of the problem can be far more important than initially realised.

Such adaptive and unstructured mesh techniques are applied with great success in many fields and it seems wise to investigate their use in physical oceanography, to study their strengths and weaknesses, and try to further develop and tailor their use here. This work is ongoing within the development of the non-hydrostatic finite element ocean model ICOM by the team listed above. For further discussions and details see Pain et al., 2005; Piggott et al., 2007b.

Adaptive and unstructured meshes

Unstructured meshes have found widespread use in a variety of application areas – especially those where the accurate representation of complex domains is important, e.g. in industrial computational fluid dynamics (CFD). Unstructured meshes are more flexible than structured grids since they can be connected in arbitrary ways and can be locally refined without resulting in hanging nodes. For example, a triangle may be split into three smaller triangles through the addition of a single extra node in the initial triangle's interior. An example of an adaptive mesh simulation is given in Figure 2 (page 22) where flow in a lid-driven cavity has been simulated. This is one of many well studied CFD problems that have data available and can contribute to the validation of a new model. This is one advantage of basing ICOM on a 3D Navier-Stokes solver kernel – one may make use of these problems for testing the core discretisation, additional aspects such as adaptivity, error measures, turbulence models, etc. An example of an idealised geophysical problem where rotation and buoyancy are important is given in Figure 3 (page 22). Further examples may be found in Pain et al., 2005; Piggott et al., 2007a; Piggott et al., 2007b.

The initial mesh generation procedure is an opportunity to begin optimising the overall calculation. Figure 1 shows a section of a mesh generated to represent the bathymetry of the North Atlantic. Notice that areas of increased bathymetry roughness benefit from enhanced resolution, marginal seas remain connected, and a staircase representation has been avoided. By considering the depth of the ocean, as a local function of x and y, one is able to optimise its representation by considering mesh generation as an interpolation problem where the error is minimised using variable resolution. Here this equates to placing increased resolution in regions of high bathymetric curvature.

This leads on to the important issue of anisotropy in the error measure and mesh. Curvature is a directional quantity, so for example one will have higher curvature across features such as shelf breaks and regions of shear in the flow. By basing error measures on quantities with directional information one is able to build anisotropic meshes and so further optimise the use of computational resources. As an example, boundary layers (e.g. in Figure 2) are an important process that benefits from the use of anisotropic elements where increased resolution is required in the direction normal to the boundary and less is required tangentially.

The technique used here to adapt the mesh is based upon an optimisation approach where local operations are performed on the mesh to alter the size and shape of elements measured in a metric obtained from the error measure. The optimisation algorithm considers a finite set of local topological mesh operations which seek to minimise this functional. The operations employed here include edge splitting and collapsing which respectively refine and coarsen the mesh. Edge and face swapping algorithms are also included and play an important role in achieving appropriately shaped elements.

Mesh optimisation can lead to large load imbalances when computing in parallel, the total number of nodes on processors and hence the local computational cost can vary widely. Therefore, mesh optimisation methods must incorporate dynamic load balancing methods in order to maintain parallel efficiency.

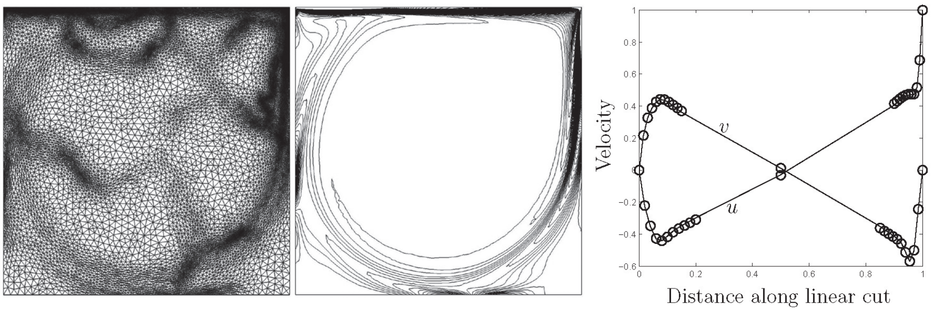

Figure 2: Adapted mesh (left) and vorticity contours (centre) in driven cavity flow at Reynolds number 5000. Comparisons of the model velocities in linear cuts across the centre of the domain (the continuous lines in the figure right) are made with tabulated data (circles) from Erturk et al., 2005. This computation has been conducted in a quasi-2D manner, i.e. is thin in the direction into the page, and uses approximately 50,000 nodes. The minimum element edge length (occurring in the boundary layer at the top of the domain) is 30 times smaller than the largest edge length in the mesh, and if used throughout the domain would result in a mesh of 1M nodes in 2D.

Continuous mesh movement is an important extension to the discrete optimisation approach described above. It lacks robustness when used alone since the total number of degrees of freedom in the discretisation is fixed and mesh tangling can occur. However, it does have many advantages when modelling problems where Lagrangian solution structures are important. In ocean modelling an immediate application of this extension is to move the mesh to resolve vertical density structures while minimising spurious diapycnal mixing – an analogue of the use of isopycnal coordinates in a model.

Some problems and solutions

There are obviously many challenges that must be addressed when applying new numerical methods to a particular application area. The techniques introduced above have been used and validated in various computational fluid dynamics areas. These have generally been at scales where the effects of buoyancy and rotation are of less importance than they are in oceanography. For robustness of the underlying discretisation in ICOM much work has gone into enabling the model to accurately and stably represent states close to hydrostatic and geostrophic balance.

Once a robust discretisation algorithm has been developed, the next problem is how to ensure the mesh is adapted appropriately to improve a calculation. A first stage is to use error ‘indicators’ such as curvature (or Hessian) based metrics which yield directional information and are good at indicating areas of complexity in the flow, Piggott et al., 2005. A more powerful approach is the so-called goal-based method where the mesh is adapted to optimise the accuracy to which a goal functional – a physical quantity of interest, e.g. lift and drag in aerodynamics, or poleward heat transport in the ocean – is computed, Power et al., 2006.

Most ocean models distinguish between the horizontal and vertical in the mesh structure and discretisation, with columns in the mesh in the vertical for example. The approach taken here is to use a mesh unstructured in 3D. This will undoubtedly have advantages for the representation of overflows or bottom boundary layers for example. But in some parts of the ocean a columnar mesh may be most appropriate. Whilst the 3D unstructured mesh approach includes columnar meshes as a special case and could be restricted to achieve this, it will be interesting to see if certain error measure choices allow this behaviour to emerge naturally. One reason for preserving interest in columnar meshes is that many subgrid-scale models assume this structure. Even with adaptive resolution subgrid-scale models are still necessary, but now of course the definition of what length scales are subgrid varies throughout space-time and this must be taken into account in the models – as LES models do for example.

Other important aspects that must be considered when using an adaptive mesh include the interpolation of quantities from one mesh to another, and the construction of an adjoint model. Here the amount of interpolation performed is minimised as the operations altering the mesh are local in nature. It is further reduced when mesh movement accounts for some of the resolution changes since the movement of the nodes can be accounted for by discretising the underlying equations in a moving reference frame. However, some interpolation is inevitable, this also includes interpolation from atmospheric models, and perhaps between different meshes used to represent biology or sediments for example. This is currently under investigation. With regards the construction of an adjoint model, once the use of an inconsistent approach has been accepted, one is able to use a different mesh adapted to the adjoint solution fields for the adjoint calculation, and also to use a hierarchy of meshes to accelerate the data assimilation procedure, Fang et al., 2006.

Ongoing and future work

Current developments are focusing on new higher-order element types to achieve more accurate and stable discretisations, error measure development, combined mesh optimisation and movement, subgrid-scale models, data assimilation. An opensource development approach is being pursued with opensource libraries being used and extended for linear solvers and preconditioners, visualisation, diagnostics, data and meta-data storage and manipulation, and automated build and regression testing.

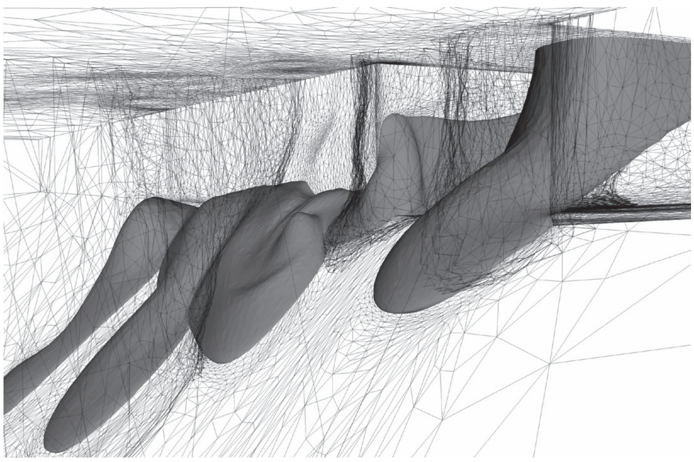

Figure 3: Adapted mesh and density isosurface in a simulation of an overflow in the presence of rotation. This simulation was performed in parallel and the mesh, shown on the surface of individual sub-domains, can be seen to be more highly refined in regions of dynamic activity.

With any new model verification and validation is of paramount importance. Here this involves the use of standard fluids benchmarks such as in Figure 2; with idealised geophysical problems studied by other models, Figure 3 for example; and with realistic simulations, global tides for example, where comparisons with other models and real world data are possible. In terms of new applications a current focus is on the wind driven and thermohaline circulation in the North Atlantic and a variety of process studies.

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Atmosphere – Ocean – Atmosphere coupling of the Southern Annular Mode

Sen Gupta, A and M H. England
Climate and Environmental Dynamics Laboratory, University of New South Wales, Australia
Corresponding author: E-mail: alexg@maths.unsw.edu.au

Introduction

Analogous to the El Niño Southern Oscillation (ENSO) phenomena in the tropical Pacific, the Southern Annular Mode (SAM) is the dominant mode of variability in the extratropical Southern Hemisphere. It is a particularly robust mode of variability, readily identified in long timeseries of observed atmospheric winds, sea level pressure (SLP) or geopotential height. It also emerges as the dominant mode in model simulations of the atmosphere and the coupled climate system (e.g. Robinson, 1991, Limpasuvan and Hartmann, 2000, Hall and Visbeck, 2002). SAM variability is characterized by zonally symmetric vacillations in the midlatitude westerlies with a strengthening and poleward shift (a positive SAM phase) or a weakening and equatorward shift (a negative SAM phase) in the winds. The anomalous SAM winds extend from the surface to the upper troposphere. While other work has shown that unlike ENSO, the SAM can be explained by purely atmospheric mechanisms, its strong surface signature can significantly affect the ocean and sea-ice systems below. Work by Hall and Visbeck (2002), first suggested that a zonally symmetric SAM pattern is also evident in surface ocean properties as a result of dynamical and thermodynamical forcing from the atmosphere. SAM induced changes in high inertia oceanic properties can persist for timescales exceeding the original atmospheric anomaly and have the potential to re-imprint a signature back to the atmosphere, thereby altering the characteristics of the SAM. The study of the SAM has taken on a new urgency as an increasingly clear trend towards a more positive phase has been observed over the last few decades (e.g. Kushner, et al 2001; Thompson and Solomon, 2002).

Here we use reanalysis datasets in conjunction with output and model simulations from the NCAR CCSM coupled climate model to investigate the mechanisms associated with the SAM that create robust oceanic anomalies. We also demonstrate that a feedback mechanism from the ocean to the atmosphere is indeed important in determining the SAM's temporal characteristics.

Oceanic response to SAM

Fig. 1 (from Sen Gupta and England, 2006a) shows a schematic of anomalous atmospheric and oceanic properties during a positive SAM event. In the atmosphere a westerly anomaly at high latitudes and an easterly anomaly at lower latitudes cause a poleward shift (and a strengthening) of the mean westerly flow. At the surface, frictional forces break the geostrophic balance giving rise to a meridional component to the wind and a surface divergence near 45°S. This results in downward air flow and an associated atmospheric adiabatic warming at

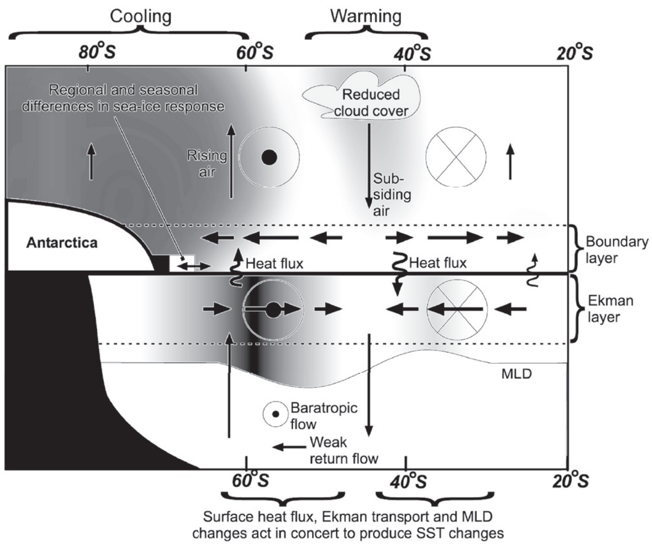

Figure 1. Schematic representation of the effect on the climate system for a positive SAM. The schematic of circulation, properties and fluxes for the negative phase of the SAM exhibits the same patterns as displayed above, only with reversed directions of circulation and the opposite sign for property anomalies and fluxes. High-latitude dark-grey shading indicates regions of atmospheric/oceanic cooling while lower latitude light-grey shading represents warming.

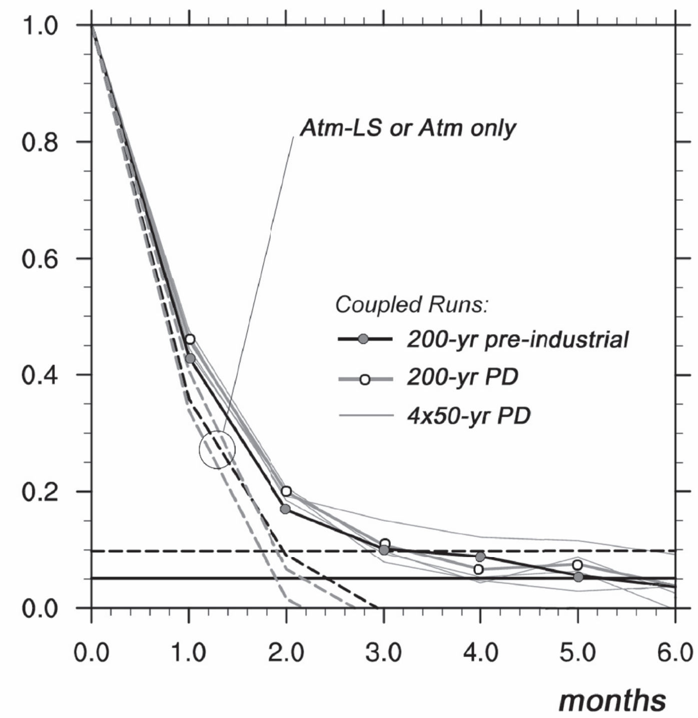

Figure 3. (a) Autocorrelation of the SAM index for two 200-year coupled control integrations: present day (PD, continuous thick grey) and a pre-industrial (continuous black) and for three 50-year uncoupled experiments w ith prescribed ocean/ice (dashed lines). Thin grey lines show results for PD timeseries broken into 4x50year sequential subseries for comparison with the uncoupled runs. The 95% confidence intervals are also shown (horizontal lines – lower line for coupled 200yr experiments, upper line for 50 yr experiments).

these latitudes. A compensating upward flow occurs at higher and lower latitudes.

The anomalous surface winds drive an Ekman flow in the surface ocean with both zonal and meridional components. The zonal component tends to strengthen and shift poleward the surface eastward circulation – mirroring the change in the westerly winds in the atmosphere. The anomalous meridional circulation redistributes heat, creating warmer sea surface temperatures (SST) to the north and colder SSTs to the south of 45^{o}S. Interestingly the modified heat advection acts in phase with changes in surface heat fluxes over much of the Southern Ocean to enhance the SST response to the SAM. This is demonstrated in a mixed layer heat budget (Fig. 2). The zonal symmetry of the SST response is further enhanced by changes in the mixed layer depths associated with the SAM (Fig. 1). The anomalous meridional surface circulation also leads to a zonally symmetric divergence and convergence that produce an anomalous vertical circulation. In this way the atmospheric SAM can almost instantaneously affect the meridional overturning circulation and in fact a large portion of the Deacon Cell variability can be explained by the SAM. There is also an anomalous rearrangement of sea surface slope that increases the eastward barotropic flow at midlatitudes. Through the Drake Passage, for instance, the anomalous transport is enhanced by 3.5 Sv for a 1 standard deviation SAM in the coupled model. This compares well with observations of a 4 Sv increase (Hughes et al. 2003). In general the CCSM atmospheric and surface circulation response to the SAM is in close agreement with observations (see Sen Gupta and England, 2006a for further details). The thermal response however is overestimated and more zonally symmetric than the available observations suggest.

Atmospheric feedback associated with ocean coupling

While the large scale atmospheric SAM response decays relatively quickly, the oceanic response can persist for many months (Sen Gupta and England, 2006a). This in turn increases the persistence of surface air temperatures. Autocorrelations of the SAM index (which, like the Southern Oscillation Index for ENSO, characterises the strength and polarity of the SAM) are presented for a number of atmosphere-only, atmosphere-land and fully coupled integrations of the CCSM (Fig. 3, from Sen Gupta and England, 2006b). Immediately evident is the enhanced persistence of the SAM when active ocean and sea-ice models are coupled to the atmosphere. Studies of Northern Hemisphere extratropical ocean-atmosphere coupling (see review by Kushnir et al. 2002) also find this increased persistence in atmospheric modes when the oceanic feedback is considered. Two mechanisms may be important. First, by introducing an oceanic thermal response, atmospheric anomalies will be subject to weaker thermal damping, this may in turn reduce the damping of the atmospheric SAM. Alternatively the thermal response in the atmosphere to the anomalous SST may interact non-linearly with the mean atmospheric circulation to re-excite the SAM. Recent work using ensemble perturbation experiments in both atmosphere-only and fully coupled models (Sen Gupta and England, 2006b) suggest that both these mechanisms could be playing a part in the persistence of the SAM to time-scales of seasons and beyond.

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Spanish research activities on climate variability and predictability: the CLIVAR–España network

R. Boscolo[1] and CLIVAR– España Steering Committee*
[1]ICPO, National Oceanography Centre, Southampton, UK/IIM–CSIC, Vigo, Spain
Corresponding author: rbos@iim.csic.es

The CLIVAR-España network (http://clivar.iim.csic.es/) was constituted/launched in early February 2004 with the aim of:

- promoting climate research in Spain, using the scientific network as a platform to foster CLIVAR research areas and encourage the participation of Spanish scientists in international CLIVAR activities
- publicising the relevance of CLIVAR research in different national socio-economic contexts (population quality of life, ecosystems, agrosystems, energy, water resources, fisheries, aquiculture, etc.)
- disseminating information on CLIVAR research among the scientific community, facilitating access to publications and data

The network includes 50 research groups from universities, National Research Institutions (CSIC, IEO, CIEMAT,etc.) and other organisations (Spanish Meteorology Institute, Spanish State Ports Agency). It receives funding from the Spanish Ministry of Education and Science.

In February 2005 CLIVAR-España organized a workshop in Madrid to facilitate the beginning of a process aimed at identifying and quantifying the strengths and weaknesses of climate research in Spain, and pinpointing the most relevant factors required to promote future progress.

The meeting was structured around six themes:

- Global atmospheric variability
- Climate variability over the Iberian Peninsula
- Modelling and prediction at regional scale
- Oceanic variability
- Paleoclimate
- Databases available

The workshop provided for the first time a multidisciplinary forum for exchange of information and discussions among the various research groups working on different aspects of climate variability and change in Spain. Amongst other factors, aspects such as the level of co-ordination between groups and current levels of support by the institutions among other factors were analyzed with the aim of finding solutions for improvement.

The main outcomes of the workshop and the ensuing discussions are summarized in a document that was recently published by the CLIVAR-España network. The document is entitled "The state-of-the-art of Climate Research in Spain" and is available in both Spanish and English at the CLIVAR-España webpage: http://clivar.iim.csic.es/. It describes how climate research in Spain has evolved over the last decade. Several research groups have made substantial contributions to the understanding of regional climate and its predictions, and the number of scientists, international publications and projects in the fields of climate variability and predictability has increased steadily.

The last IPCC report indicates that Spain might be especially vulnerable to the consequences of human-induced expected increases in radiative forcing arising from increased levels of greenhouse gas concentrations. Model projections under future emission scenarios indicate that the Iberian Peninsula could experience a 20% decrease in summer precipitation. Under such a threat it is imperative to reduce negative impacts by developing effective mitigation and adaptation strategies. Such strategies need to be based in a good knowledge of the regional past and present climate dynamics and variability. By giving a high priority to climate research in accordance with its economic status and its potential vulnerability, Spain can face this challenge.

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"Arise Sir Brian"!

Congratulations to Brian Hoskins, from the University of Reading who has been recognised on the Queen's Birthday Honours List for the second time. Professor Sir Brian Hoskins, CBE, FRS, was knighted for his services to environmental science.

CLIVAR Atlantic Implementation Panel: 8th session

Boscolo, R and W. Hazeleger, CLIVAR Atlantic Implementation Panel
Corresponding author: rbos@iim.csic.es

The 8th session of the CLIVAR Atlantic Implementation Panel (AIP) was held in Kiel, Germany, on 21-22 March 2007. The panel meeting followed the CLIVAR workshop on the North Atlantic Subpolar Gyre (http://www.ifm-geomar.de/index.php?id=subpolar-gyre). The last session of the workshop entitled "Past, present and future perspectives of Subpolar Atlantic variability in the CLIVAR context" overlapped with the beginning of the AIP meeting thus giving the first focus to the panel discussions. With the end of the 10-year German programme on the study of the dynamics and interactions of the subpolar gyre with the regional and global climate system, emphasis was placed on the need to define future coordinated efforts in the region with regards to process studies, sustained observations, modelling experiments and reanalysis.

Implementation of CLIVAR in the Atlantic sector
The ongoing observations in the Atlantic sector were assessed. Drifter and float coverage is good in general and the basin-wide heat content variability is adequately monitored by Argo. The time series at key locations in the Nordic Seas provide an adequate monitoring of water masses changes, overflows and MOC variability. However it was strongly recommended that overflow monitoring and Atlantic-Arctic freshwater inflow measurements should continue. Particular attention and planning is needed for improvement of surface fluxes and key satellite measurements.

The accomplishments of the PIRATA array for the period 1997-2005 were reviewed by CLIVAR and OOPC. Both supported the continuation of PIRATA as the backbone of the Tropical Atlantic observing system and recommended the array to be integrated with other projects taking place in the tropical Atlantic. In order to move from a research-based, time-limited observing initiative to a sustainable observing system, PIRATA should become part of an internationally sponsored ocean observing system and integrated into research projects leading to better state-estimation and predictions.

The strategy for Atlantic MOC monitoring was discussed. After the impressive results from the first year of 26.5N data, the UK RAPID programme obtained full support to continue this activity until 2013. The objectives for the RAPID follow-on programme, called RAPID-WATCH, are:

- To deliver a decade-long time series of calibrated and quality-controlled measurements of the Atlantic MOC from the RAPID-WATCH arrays
- To exploit the data from the RAPID-WATCH arrays and elsewhere to determine and interpret recent changes in the Atlantic MOC, assess the risk of rapid climate change, and investigate the potential for predictions of the MOC and its impacts on climate.

An initiative led by NOAA is seeks to bring together scientists with current or proposed programmes in the South Atlantic with the main goal to foster collaborations on the establishment of a monitoring system for meridional heat and mass transports in the South Atlantic as a component of the Meridional Overturning Circulation. A workshop entitled "A monitoring system for heat and mass transports in the South Atlantic as a component of the MOC" was held in Buenos Aires on 8-10 May 2007 (http://www.aoml.noaa.gov/phod/SAW).

Both modeling and observational elements of the Tropical Atlantic Climate Experiment (TACE, http://www.clivar.org/organization/atlantic/atlantic.php) are well underway. The TACE modeling and synthesis working group is proposing a series of experiments for understanding the physics that determines the mean and seasonal cycle of the Atlantic ITCZ (AITCZ), while the TACE observations working group (http://tace.ifm-geomar.de/index.html) is helping design an optimal observing system for the tropical Atlantic and determining the necessary sustained observation network in order to meet future climate forecasting needs. TACE together with AMMA-Ocean and PIRATA will hold a meeting during the International AMMA Conference 26-30 November 2007, Karlsruhe Germany, to discuss the role of the Tropical Atlantic Ocean in the climate system. Meeting sessions will be devoted to the following topics:

1) Atlantic ITCZ and Tropical Atlantic Variability
2) Air-sea coupling, sea surface temperature & ocean mixed layer heat budget
3) Prediction and predictability of tropical Atlantic variability
4) Tropical ocean circulation (including oxygen minimum zones, Tropical Intermediate Waters and equatorial wave dynamics)

Planning has also started for the joint AIP-VAMOS Southwestern Atlantic climate Variability Experiment (WAVEs). WAVEs aims to study the physical mechanisms that cause the SST variability on intraseasonal to interdecadal timescales in the South Western Atlantic. The proposal includes field experiments and coupled modelling studies on ocean-atmosphere-biosphere interactions leading to South Western Atlantic - South America climate variability and change.

An overall strategy for validating the synthesis products was addressed. The chair of CLIVAR Global Synthesis and Observation Panel reported on several ocean data assimilation products and highlighted the importance of evaluation efforts in order to assess their quality and usefulness for climate research. The AIP recognized that primary issue is to identify the key variables that needed to be observed in order to constrain climate predictions and discussed which elements should be part of a sustained Atlantic Ocean climate observing system. Among those platforms that provide good coverage, cost and deployment effectiveness and relevant information content, the following were mentioned: full depth ARGO floats, altimetry, scatterometry winds, a combined system for SST and sea surface salinity.

Future perspective of CLIVAR in the Atlantic sector
The AIP was informed of several activities in US and Europe focusing on decadal predictability. The rational behind these lies on the linkage suggested by models between multi-decadal (perhaps decadal) SST variability and the Atlantic MOC together with the relevant societal consequences (hurricane activity, droughts etc.). The AIP suggests decadal predictability to be one of the main foci for CLIVAR. Widespread acceptance of climate change is generating growing demand for the best possible information about near term, regional climate trends. This information is needed to inform adaptation decisions. It is on decadal timescales and regional spatial scales that internal variability and externally forced trends have comparable amplitude which implies that fluctuations can reverse local trends. Decadal predictions could be further helpful for detecting climate change. They could potentially separate the impacts of the internal climate variability from the impacts of

anthropogenic emissions of greenhouse gases and aerosols. On the decadal time scale emission scenario uncertainty is not the dominant factor in the uncertainty for near (decadal) predictions, but initial state (mainly oceanic) and model uncertainty is. The Atlantic sector provides a natural focus for the decadal prediction problem and the AIP could play a role in providing the link between earth observations and detection, attribution and prediction of climate variability and change.

FROM THE CALENDAR – for more details see http://www.clivar.org/calendar/calendar_all.php

MEETING	DATES		WHERE		CONTACT	
US CLIVAR Summit 2007	2007-07-23	2007-07-25	Annapolis, MD	USA	Cathy Stephens	cstephens@usclivar.org
Celebrating the Monsoon	2007-07-24	2007-07-28	Bangalore	India		mon_2007@caos.iisc.ernet.in, celmon2007@yahoo.co.in
AOGS 4th Annual Meeting - Session on Asian-Australian Monsoon/Indo-Pacific Climate Variabilities	2007-07-30	2007-08-04	Bangkok	Thailand	Tim Li, Tianjun Zhou, Jianyin Liang	timli@hawaii.edu, zhoutj@lasg.iap.ac.cn, liangjy@cma.gov.cn
PAGES Scientific Steering Committee Meeting	2007-07-31	2007-07-31	Cairns	Australia	PAGES IPO	pages@pages.unibe.ch
1st International ARCNESS Winter School	2007-08-13	2007-08-17	Wollongong	Australia		
ECORD Summer School on Paleoceanography	2007-08-13	2007-08-24	Bremen	Germany	Uta Brathauer, Gerold Wefer	gratmeyer@marum.de
North Atlantic and Arctic Climate Variability	2007-08-15	2007-08-16	Bremen	Germany		
10th International Meeting on Statistical Climatology	2007-08-20	2007-08-24	Beijing	China	Xuebin Zhang	Xuebin.Zhang@ec.gc.ca
Layered Ocean Model (LOM) Meeting	2007-08-20	2007-08-23	Bergen	Norway		helge.drange@nersc.no
15th AMS Conference on Air-Sea Interaction	2007-08-20	2007-08-24	Portland	USA		
Workshop on Numerical Methods in Ocean Models	2007-08-23	2007-08-24	Bergen	Norway	Anna Pirani	Anna.Pirani@noc.soton.ac.uk
7th Session of the Working Group on Ocean Model Development	2007-08-25	2007-08-26	Bergen	Norway	Anna Pirani	Anna.Pirani@noc.soton.ac.uk
SCOR Executive Committee Meeting	2007-08-26	2007-08-28	Bergen	Norway		
3rd Alexander von Humboldt International Conference on The East Asian Summer Monsoon, past, present and future	2007-08-27	2007-08-31	Beijing	China	Prof. A Berger	berger@astr.ucl.ac.be
Second International Conference on Earth System Modelling	2007-08-27	2007-08-31	Hamburg	Germany	Dr. Annette Kirk	mpi-conference2007@zmaw.de
Polar Dynamics: Monitoring, Understanding and Prediction	2007-08-29	2007-08-31	Bergen	Norway		conference2007@gfi.uib.no

ICPO News – Farewell to Mike

Following 6 years with the ICPO, Mike Sparrow has decided to move on to join the Secretariat for the Scientific Committee for Antarctic Research in Cambridge UK. In his work for CLIVAR, Mike has been responsible both for the CLIVAR/CliC/SCAR Southern Ocean Region Panel and, over the last 18 months, for the CLIVAR Variability of the African Climate System Panel and has made a considerable contribution to the management of both of these Panels. In addition Mike has been responsible for bringing the WOCE Atlases to publication, the finalization of which he takes with him. Mike's experience, skills, dedication and sense of humour will be sorely missed by all of us within the ICPO. We wish him well in his new post and look forward to continuing to interact with him in a SCAR context. For the present his ICPO duties will be covered by Nico Caltabiano.

Howard Cattle

Contents

Call for Contributions

We would like to invite the CLIVAR community to submit papers for CLIVAR Exchanges for issue 43. The overarching topic will be on Seasonal Forecasting. The Deadline for this issue will be 14th September 2007.

Guidelines for the submission of papers for CLIVAR Exchanges can be found under:
http://www.clivar.org/publications/exchanges/guidel.php

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International CLIVAR Project Office
National Oceanography Centre Southampton
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Southampton, SO14 3ZH, United Kingdom
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