AusCOM: The Australian Community Ocean Model

Jason Roberts

Tasmanian Partnership for Advanced Computing,
and Antarctic Climate and Ecosystems CRC,
University of Tasmania, Private Bag 37, Hobart, Tasmania, Australia, 7001
J.L.Roberts@utas.edu.au

Petra Heil

Australian Government Antarctic Division,
Channel Highway, Kingston, Tasmania, Australia, 7050
and Antarctic Climate and Ecosystems CRC,
University of Tasmania, Hobart, Tasmania, Australia
Petra.Heil@utas.edu.au

Steven J. Phipps

Tasmanian Partnership for Advanced Computing,
sjphipps@utas.edu.au

Nathan Bindoff

Tasmanian Partnership for Advanced Computing,
and Institute of Antarctic and Southern Ocean Studies,
and Antarctic Climate and Ecosystems CRC,
University of Tasmania, Hobart, Tasmania, Australia
and CSIRO Marine and Atmospheric Research,
Castray Esplanade, Hobart, Tasmania 7000,
n.bindoff@utas.edu.au

The Australian Community Ocean Model (AusCOM) is an initiative by the Australian climate sciences community (including government and academic research laboratories) towards a unified coupled ocean-seaice model for climate applications. The technical configuration and details of the sub-models are presented here. Initial results, and the development of a displaced pole bipolar ocean grid are discussed. An outlook for future model development is given.

ACM Classification: J2

1. INTRODUCTION

Future anthropogenic climate change has the potential to impact significantly on Australia and its territories, with profound consequences for Australian society and its economy. The Australian economy has a significant dependence on agriculture and fisheries, both of which are likely to be adversely impacted by climate change. A recent estimate of the potential total economic cost of climate change to Australia was between 1.2% and 3.8% of gross domestic product (Basher *et al*, 1998).

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Climate change will not only modify the mean state of the climate, but will also adversely change the likelihood of extreme events (McCarthy *et al*, 2001), with an increase in the incidence of bushfires and flooding, both of which have societal impacts far exceeding their financial impacts.

Clearly there is a need for detailed understanding of future climate, its associated variability and impacts, in order to better prepare and manage resources in a sustainable way for future generations, for example fisheries management, agricultural policy and bushfire management.

Future climate change and variability can be investigated via computer models, which are comprehensive, high-resolution numerical simulations of the climate system. Comprehensive in this context means sub-models for atmosphere, ocean, cryosphere (glacial and sea-ice), terrestrial, chemical and biological environments. Each of these systems are non-linear with current computer model implementations running to many tens of thousands of lines of code, for each individual type of sub-model. However, the Earth is a complex system where the physics (for example) does not partition itself into neat independent components (Adlen *et al*, 2003), so these sub-models need to be coupled to allow for interactions outside of the somewhat artificially imposed components. A coherent Earth system model requires a generic coupler able to provide complete spatial and temporal integration of all the sub-models in a numerically consistent way and incorporate all of the associated feedbacks. This coupling represents a challenging task for integrated Earth systems modeling (Adlen *et al*, 2003).

Climate variability and change are determined by interactions between the physical processes and the carbon cycle. One of the key gaps in understanding climate change is the lack of effective links between physical and biogeochemical models (Houghton *et al*, 2001). In particular, sources of uncertainty on climate change impacts on Australia include the regional effects of biosphere feedbacks (McCarthy *et al*, 2001; Australian Greenhouse Office, 2003). There is also a need to integrate human activity models into an integrated climate systems model (Houghton *et al*, 2001). There are significant gaps in the knowledge base associated with climate change, including regional scale climate influences and responses and the detection and attribution of climate change on a regional basis (Australian Greenhouse Office, 2003). Australia has the only major climate prediction program in the Southern Hemisphere, and it is known that Southern Hemisphere climate processes differ significantly from those of the Northern Hemisphere (Australian Greenhouse Office, 2003).

AusCOM is an initiative of Australian government and university research groups to standardise a subset of these models, namely the ocean and sea-ice models, for climate applications. This coupled core model will then be expanded for the more comprehensive suite of models in the ACCESS project discussed in Section 5.

The development of AusCOM will result in many benefits to this research community including: (a) reducing the number of large complex codes requiring support; (b) having a broader range of local expertise available; (c) having simulation output available from a variety of institutions - potentially reducing the computational cost of a series of simulations as some of the simulations might have been conducted elsewhere; and (d) simplifying the ability to use the computational and data grids to conduct simulations - as only one main code needs to be modified to run in these environments. Additional benefits may arise, for example, from sharing of data analysis and graphical handling tool scripts. This standardisation is non-exclusive in nature, some simulations may require a model configuration outside the AusCOM specification (in fact may require a completely different model), but the research community is encouraged to use an AusCOM conforming specification where appropriate to allow for direct inter-comparison between simulations. The benefit of sharing simulation results, where appropriate, is highlighted by the computational cost of an ocean simulation. For AusCOM (the model resolution is described later) 1104 cpu hours on an 1.6 GHz Itanium2 SGI Altix 4700 system are required to simulate one year.

2. MODEL FRAMEWORK

AusCOM is designed to be a modular model, where any sub-model can be updated or replaced easily, with minimal impacts on the other sub-models. The main impacts occur where boundary condition data are exchanged between sub-models. Each of the sub-models is written in FORTRAN 90, because compilers are readily available on a wide range of computational platforms offering good execution performance and the easy treatment of multi-dimensional arrays in FORTRAN make it a programming language of choice for climate scientists.

To allow for long integrations (simulations of millennial scale processes) and ensemble simulations, each sub-model, and the coupled model, must be capable of parallel execution and ideally scale to tens of processors efficiently. Therefore, all sub-models are internally parallelised using MPI. Furthermore, memory requirements of the individual sub-models may exceed the available memory on many target systems. Domain decomposition, provides a mechanism to reduce the per processor memory requirements.

A numerical coupler has been used to achieve modularity, with all information exchanges between the sub-models being strictly via a coupler utilizing MPI communicators. Advantages associated with the use of a numerical coupler include:

1. **Modular Architecture**
   The ability to have individual sub-model executables and model grids means that any sub-model can be replaced by an alternative sub-model of differing complexity easily. This allows for sensitivity studies, for example how sensitive is the coupled model to processes included in a particular sea-ice model.

2. **Individual Sub-model Executables**
   Using MPI communication to exchange information means that each model can be separately compiled into its own executable. All that is required is that all of the executables are launched with the same "mpirun" command. This greatly simplifies the compilation process and means that a code developer only needs to be familiar with a single code (providing that none of the development work changes the inter-model communications).

3. **Expandability**
   Additional models can be (relatively) easily added. For example, land surface models or river run-off models can be added to improve the ocean simulations by introducing realistic sources of fresh water. In fact while AusCOM consists of ocean and sea-ice models and the numerical coupler, boundary conditions are supplied through a data atmosphere model, which includes an atmospheric boundary layer model (see Section 3.4) so that inclusion of a numerical atmosphere model is easily achieved by replacing this data model.

4. **Grid Independence**
   The ability of the numerical coupler to conservatively interpolate between different grids at the two-dimensional (in spherical coordinates) interface between the sub-model domains means that each sub-model can use the most physically, numerically and computational appropriate grid for simulations. This is particularly relevant when AusCOM is coupled to a numerical atmosphere model. The grid singularity associated with the North Pole (and the associated severe restriction on the time-step for solution) can be removed for the ocean

model by transforming the grid to relocate the pole over land, and hence outside the computational domain (see Figure 1). This is not possible with an atmospheric model and other grids (such as spectral or cubic conformal grids, see Figure 2) are more appropriate.

The numerical coupler also simplifies the time-stepping used to evolve the governing equations for the various sub-models. This allows for asynchronous time stepping between models, with the restriction that all models that are exchanging information at a prescribed time must have a time-step such that the model reaches that particular time. For example, in the current set-up the ocean model has multiple time-steps. The ocean model has two internal time-steps, 6 seconds for the evolution of the barotropic system and 600 seconds for the baroclinic system and tracers. The ocean model exchanges boundary condition data with the coupler every 6 hours.

2.1 Load Balancing

Both the ocean and sea-ice models are MPI enabled for parallel execution, and use two-dimensional domain decomposition to obtain good scalability for the moderate grid resolution and hence problem size. The ocean code can run on any integer number of processors, while the sea-ice code requires the number of processors be exactly divisible by four for parallel operation. Both the coupler and data atmosphere model are uni-processor tasks. Load balancing is achieved through selection of an appropriate number of processors for each sub-model, to ensure that each sub-model reaches the synchronisation point of data exchange at approximately the same time. Both the numerical coupler and data atmosphere codes are computationally inexpensive to run, and are the

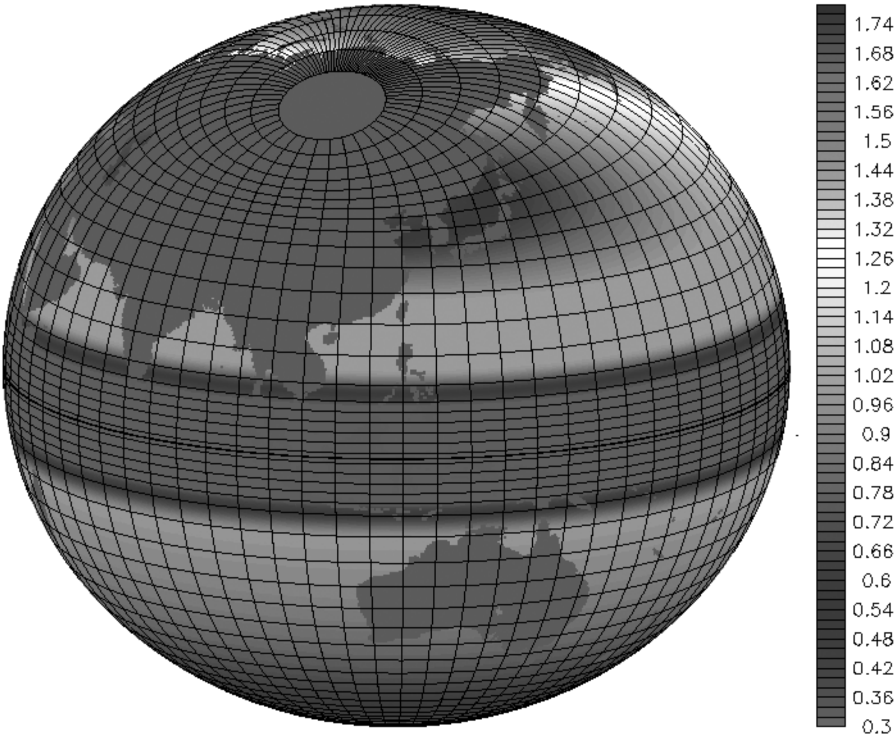


Figure 1: The default AusCOM ocean model horizontal grid is shown with its latitudinal grid spacing. Note that for clarity only every 5th grid line shown.

Figure 2: A cubic conformal grid, where a cube is mapped onto a sphere, in this case such that each face has an equal area.

dedicated processors for each of these codes is relatively idle. Parallel efficiency could be improved by having these two tasks share a processor.

3. MODEL DESCRIPTION

AusCOM consists of three components: an ocean model, a sea-ice model and a numerical coupler. Details of each of these components is given below.

3.1 Numerical Coupler

The Ocean Atmosphere Sea Ice Soil (OASIS) coupler version 3.2.3 (courtesy CERFACS) is used to exchange information between, and synchronise execution of, the model components (Valcke *et al*, 2003). Data exchange is via MPI communicators, and conservative two-dimensional interpolation is available for differing source and destination model grids. OASIS 3.2.3 has been enhanced to provide restart capabilities (see Heil *et al*, in preparation for details) so that long simulations can be preformed as a sequence of shorter simulations (suitable for execution under a queue management system). This restart capability captures any information that would be exchanged via the coupler if the simulation were to precede to the next time-step, and stores the information on disk for subsequent use at the start of the next simulation in the sequence.

Information exchange between the coupler and the sub-models is serial in the current release on OASIS, so that each parallel sub-model has to gather/scatter distributed information from/to parallel processes before exchanging the unified data with the coupler. This is inefficient, as the information is communicated twice, once between the coupler and the sub-model and once between the communication process and the other processes. Version 4 of the OASIS coupler (to be released in 2007) will overcome this limitation.

3.2 Ocean Model

The ocean component is the Modular Ocean Model (MOM) version 4p0d supplied by Geophysical Fluid Dynamics Laboratory (GFDL/NOAA Department of Commerce). This model is a finite difference, z coordinate model with generalised orthogonal horizontal coordinates, and an Arakawa B-Grid (Griffies *et al*, 2004). Time evolution of the baroclinic velocity and tracers is via either a leap-frog scheme with an associated Robert-Asselin time filter, or a newly introduced predictor-corrector scheme. The predictor-corrector scheme allows for a longer timestep (frequently double that of the leap-frog scheme) whilst maintaining stability and accuracy. Furthermore, the elimination of the time-filter when using the predictor-corrector method, significantly improves the conservation of tracers to within numerical roundoff.

The default grid for the AusCOM ocean component is a nominal 1°x1° horizontal grid (see Figure 1) with equatorial latitudinal refinement to 1/3°, Southern Hemisphere latitudinal refinement to maintain cell isotrophy with meridional grid convergence and the North Pole relocated into Siberia, as per Roberts *et al* (2006) to reduce CFL limitations on the time stepping. The vertical grid has 46 levels covering the depth range 0-5050 m with a resolution ranging from 5 m at the surface to 250 m for the abyssal ocean, Table 1 lists the vertical grid details.

3.3 Sea-ice Model

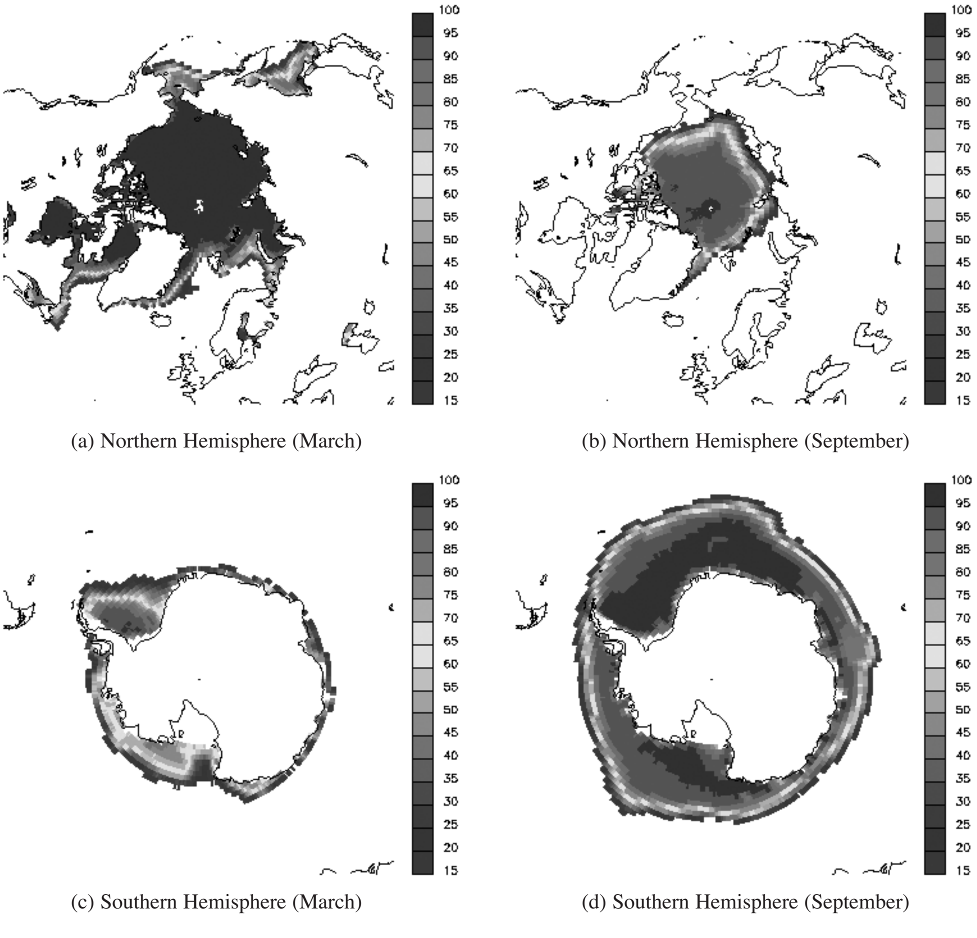
Although only covering a relatively small part of the world's oceans sea ice is an important component in the global climate system. It interacts with the ocean and atmosphere via numerous processes, and modifies the air-sea exchange. The expulsion of salt into the underlying ocean

Level	zt (m)	zw (m)	Level	zt (m)	zw (m)	Level	zt (m)	zw (m)
1	2.50	5.07	16	190.00	200.00	31	1743.06	1825.38
2	7.64	10.43	17	210.00	221.59	32	1907.71	1993.01
3	13.22	16.35	18	233.18	249.39	33	2078.32	2166.97
4	19.48	23.08	19	265.60	288.99	34	2255.62	2347.89
5	26.68	30.84	20	312.39	344.85	35	2440.17	2536.26
6	35.01	39.82	21	377.30	419.80	36	2632.34	2732.34
7	44.64	50.16	22	462.30	514.85	37	2832.34	2936.26
8	55.68	61.93	23	567.39	628.99	38	3040.17	3147.89
9	68.18	75.16	24	690.60	759.39	39	3255.62	3366.97
10	82.14	89.82	25	828.18	901.59	40	3478.32	3593.01
11	97.51	105.84	26	975.00	1050.00	41	3707.71	3825.38
12	114.18	123.08	27	1125.00	1200.31	42	3943.06	4063.29
13	131.98	141.35	28	1275.62	1351.84	43	4183.51	4305.79
14	150.72	160.43	29	1428.06	1505.79	44	4428.06	4551.84
15	170.14	180.07	30	1583.51	1663.29	45	4675.62	4800.31
						46	4925.00	5050.00

Table 1: AusCOM ocean vertical grid distribution, showing the node depth for tracers (z_t) and vertical velocity (z_w).

associated with the sea-ice formation, and the profound reduction of albedo (relative to open ocean) present the most dramatic consequences of sea ice within the polar climate system. Figure 3 shows the observed sea-ice concentration during the annual maximum and minimum for both hemispheres. Using remotely sensed data (Cavalieri *et al*, 1997) the maximum sea-ice extent of the Arctic is estimated to average at 15.6 10^6 km^2, while the averaged maximum sea-ice extent for the Antarctic sea-ice region is 18.4 10^6 km^2. Seasonal variations are significant: minimum and maximum sea-ice extent differ by 75% in area in the Antarctic but by only about 50 % in the Arctic. This is a result of the difference in the latitudinal position of the sea-ice zones in the two hemispheres, and the land-locked character of the Arctic Ocean versus the divergent nature of the Antarctic sea-ice zone. This highlights the requirement to include an interactive sea-ice component into a climate model to derive realistic simulation results.

The sea-ice model used here is the Los Alamos CICE model version 3.14 model courtesy Los Alamos National Laboratory. CICE can be run as stand-alone model or in a coupled mode, so that it can be integrated into a larger framework for climate modelling. CICE is configured to be coupled to the CCSM Flux coupler from NCAR, which in AusCOM has been replaced by the OASIS



(a) Northern Hemisphere (March) (b) Northern Hemisphere (September)

(c) Southern Hemisphere (March) (d) Southern Hemisphere (September)

Figure 3: Observed sea-ice concentration (%) (Reynolds *et al*, 2002).

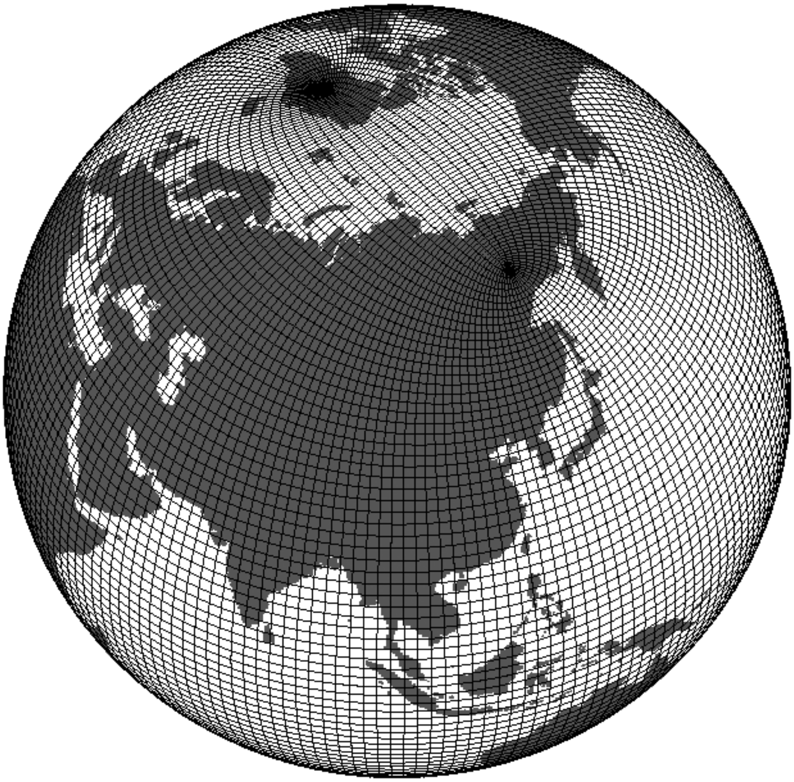


Figure 4: Alternative tripolar model grid with improved grid properties in the Artic Ocean.

coupler (see Section 3.1). The sea-ice model includes explicit calculations of the ice-dynamics, ice advection, ice-thickness redistribution, and ice thermodynamics. The user may select alternative parametrisations, where available. The model grid is an Arakawa B-Grid of global domain, i.e. the entire surface of the Earth, although obviously large areas of this domain contain only open water and no sea-ice.

In the model, sea-ice is represented as a finite number of ice-thickness categories (with the default of five ice categories in addition to open water). As such the ice-pack is modelled as a large-scale continuum within an Eulerian framework. A set of fundamental equations describes the spatio-temporal evolution of the sea-ice cover by evolving the variables of state. A elastic-viscous-plastic-yield surface is used to describe the constitutive response of the sea-ice aggregate, which can be divided into ridged and rafted ice, level (or undeformed) ice, leads and open-water areas. It is anticipated that for higher spatial resolution studies (around 10km x 10km grid) an alternative viscous-plastic yield surface will be user selectable.

3.4 Boundary Conditions

The TPAC Atmosphere Model (TPACAM) provides the surface boundary conditions to the ocean and sea-ice models via the OASIS coupler. It may be run in either an active or a passive mode. In the passive mode, TPACAM obtains the surface fluxes from either the NCEP/NCAR Reanalysis 1 or NCEP-DOE Reanalysis 2 datasets, and passes them directly to the coupler. In the active mode,

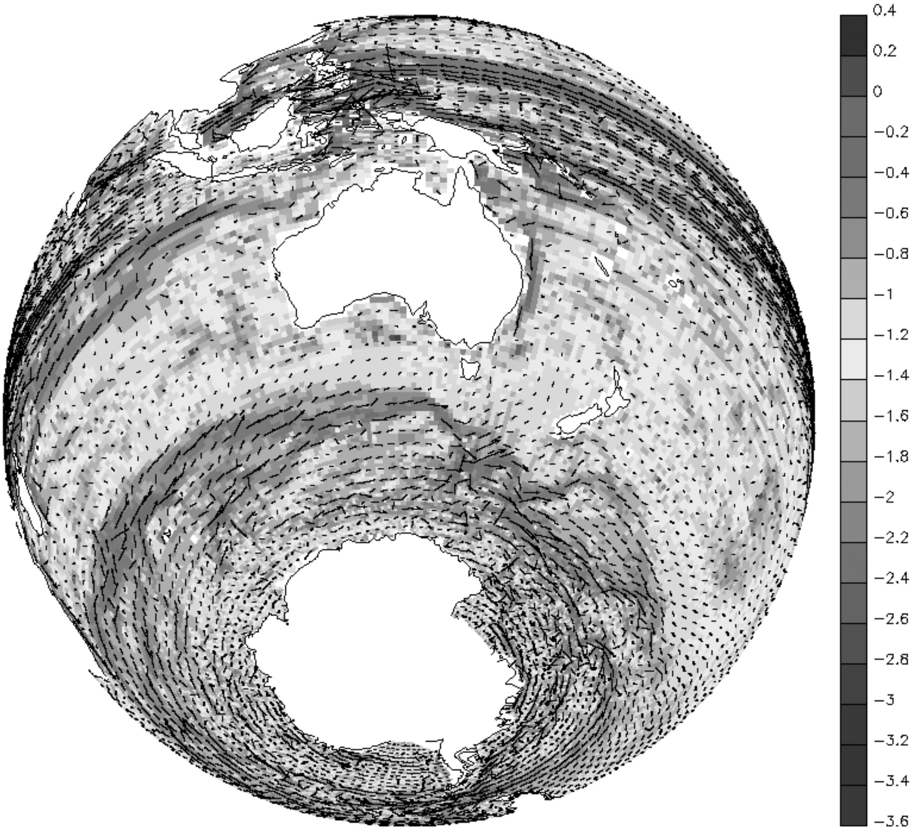


Figure 5: AusCOM ocean-only spin-up surface velocity. Shading is $\log_{10}$(surface velocity/ms^{-1}), reference vector length is 1 ms^{-1}.

however, it makes use of a simple boundary layer model (see Heil *et al*, in preparation) to calculate the surface fluxes interactively. Surface properties are obtained from the ocean and sea-ice models via the OASIS coupler, while the boundary layer model is forced from above by the NCEP-DOE Reanalysis 2.

3.5 Future Model Enhancements

While the displaced pole grid shown in Figure 1 moves the pole (and its associated numerical limitations) over land, and hence outside the computational domain, the grid in the Arctic still is a limiting factor. The grid cells in this region have a large aspect ratio, and since the smallest cell dimension limits the size of the time step for a stable simulation, this large aspect ratio is not ideal. A variant on the displaced pole grid is shown in Figure 4, in this grid the North Pole is replaced, in essence, by two poles both placed over land, leaving a tri-polar grid, where the grid south of 25°N is identical to the grid shown in Figure 1. This grid is not a standard tri-polar grid (where a bi-polar "cap" is joined to a standard latitude longitude grid and some latitude, typically around 65°N, with associated grid discontinuities) but a everywhere smooth and continuous grid where the North Pole has been numerically transformed into a line segment on the surface of the sphere that extends between the two points of grid concentration visible on Figure 4 in Siberia and Greenland.

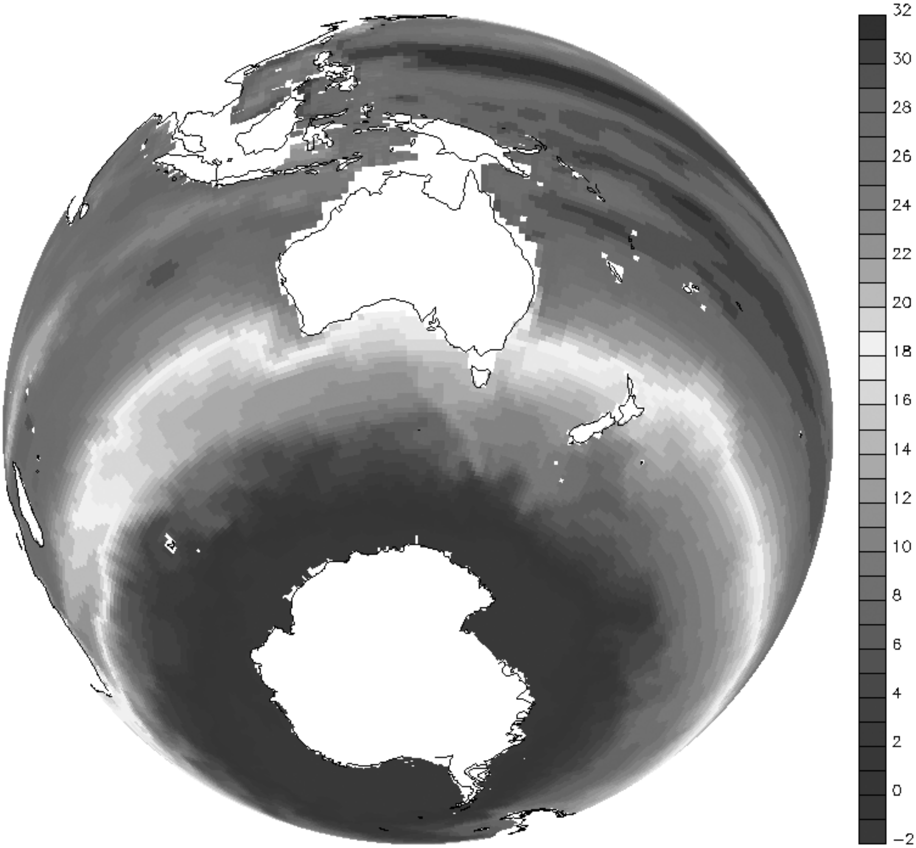


Figure 6: AusCOM ocean-only spin-up, temperature (°C) at 97.5 m.

The ocean bathymetry will need ongoing modification. At the model resolution of a nominal 1°x1° (with equatorial and Southern Ocean latitudinal refinement) many features are not properly resolved. For example, the flow through the Indonesian Archipelago is an important location of water transfer between the Pacific and Indian oceans, but the bathymetry currently used by the model is not sufficient in this region to resolve the Indo-Pacific transport well enough unless the bathymetry is manually modified.

Validation of the CICE model has largely been restricted to the Northern Hemisphere, and parameterisations used in CICE are biased to Northern Hemisphere conditions. Because the scientific focus of AusCOM is on the Southern Hemisphere, the sea-ice model does need to be validated there, which is likely to require the parameter adjustments. Limitations in the current implementation of the domain decomposition of the sea-ice model impinges on the scalability of the coupled ocean-ice system (Section 2.1). An alternative decomposition strategy will be investigated and tested on the physics of the sea-ice model.

The TPAC Atmosphere model (see Section 3.4) will be expanded to optionally include other data sets, to allow for direct study of the sensitivity of the coupled model to boundary conditions. Data sets to be added include the ECMWF ERA40 (ECMWF, 2002) and NCEP CORE (Large and Yeager, 2004) datasets.

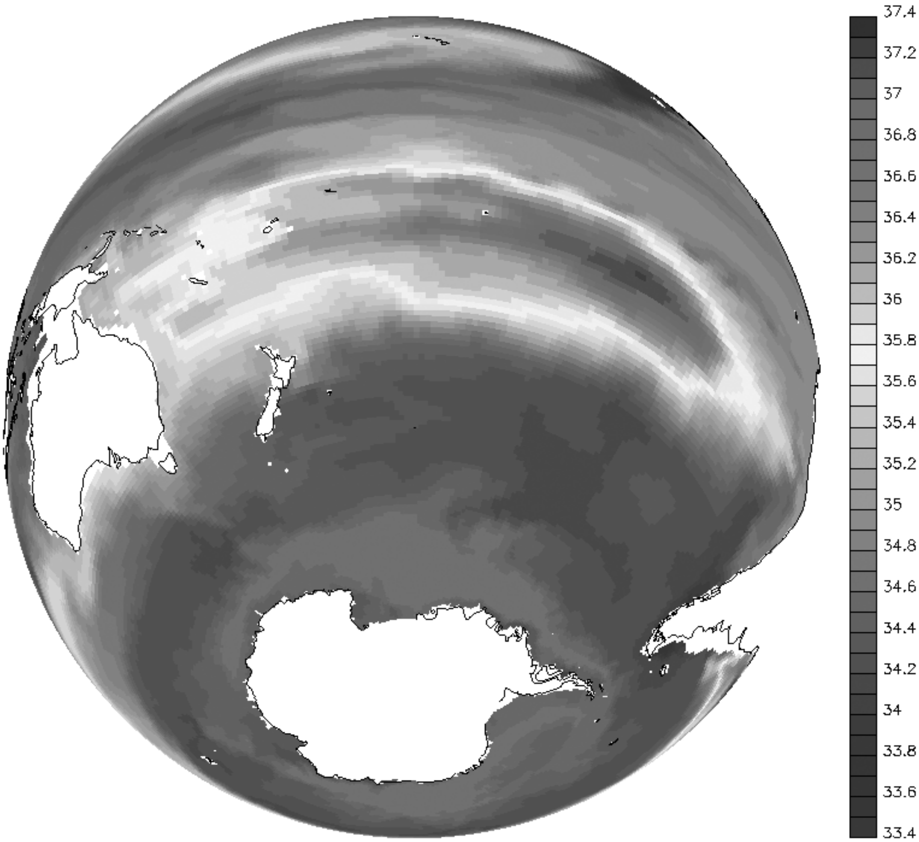


Figure 7: AusCOM ocean-only spin-up, salinity (psu) at 97.5 m.

4. INITIAL RESULTS

Figures 5–7 show initial results (all monthly averages for December 1983) for the ocean only component of AusCOM, initialised with the data from the World Ocean Atlas (Stephens *et al*, 2002; Boyer *et al*, 2002), and forced with the mean daily fields from ERA40 (1990–1999). The natural variability in the tropics and the Southern Ocean is readily apparent, as is the relative strength of western boundary currents (the strong boundary currents along the western edges of the ocean basins). The distribution at 97.5 m shows the large-scale subtropical gyres (≈30°S and 30°N) and in the equatorial band where the grid has higher resolution there is strong wave activity (Figure 6). This strong wave activity is also reflected in the salinity field (Figure 7).

5. DISCUSSION

The technical development of the Australian Community Ocean Model (AusCOM) has progressed well, with initial spin-up runs completed for the ocean component and coarse resolution runs completed for the sea-ice model. Significant improvements have been carried out on the OASIS 3.2.3 coupler. The information science component of the joining of these two sub-models through the numerical coupler has been completed, and tested with previous versions of both the ocean and sea-ice models. The remaining tasks are the adoption of a AusCOM compatible resolution for the sea-ice model and tuning the model physics in response to interactive coupling.

Project planning of AusCOM has seen a consensus being reached by the members of the involved Australian research community to jointly support a single coupled ocean and sea-ice model as the model of choice. This consensus has been expanded to include specifications of the model grid and physics, and a joint set of experiments of mutual interest. This approach has been grown with the development of the Australian Community Climate Earth Systems Simulator (ACCESS) as a joint venture between CSIRO Marine and Atmospheric Research, the Bureau of Meteorology and Australian universities. This joint venture is going to create a state-of-the-art coupled Earth System Model and associated framework for Australia, using model components in the AusCOM project plus a new atmosphere code, ocean carbon cycle, terrestrial land scheme and dynamic vegetation all coupled together into a single dynamic model. Coupled climate simulations are of a scale that demands a high level of community agreed standards. It is more critical that each components behaviour be well defined and understood. Analysis of a system as complex as the earth's climate can only be achieved with a large team of scientists working together on a common modelling framework. For Australia, this requires a multi-institutional highly distributed approach that is well served by a community model with an agreed configuration.

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The MOM4 code is courtesy of the Geophysical Fluid Dynamics Laboratory [GFDL]/NOAA Department of Commerce. The Centre Europëen de Recherche et Formation Avancée en Calcul Scientifique [CERFACS] provided the OASIS coupler (Version 3.2.3). NCEP/NCAR reanalysis data (http://www.cdc.noaa.gov/) have been obtained by the NOAA-CIRES Climate Diagnostics Center, Boulder, Colorado, USA. Computing resources at TPAC and the APAC national facility (through its merit allocation scheme) have been available to this project.

The Ferret program was used for analysis and graphics in this paper. Ferret is a product of NOAA's Pacific Marine Environmental Laboratory. (Information is available at http://ferret.pmel.noaa.gov/Ferret/)

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BIOGRAPHICAL NOTES

Jason Roberts is a climate scientist at the Tasmanian Partnership for Advanced Computing (TPAC) in Hobart Australia. He received a PhD in mechanical engineering in 1998 from the University of Tasmania, specialising in fluid dynamics. Prior to his appointment to TPAC in 2001 he worked at the Antarctic Cooperative Research Centre as an Oceanographer. His email is J.L.Roberts@utas.edu.au

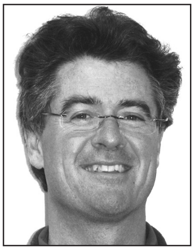
Jason Roberts

Petra Heil is a sea-ice researcher with the Australian Government Antarctic Division in Hobart, Australia. She received her PhD in 1999 from the Institute of Antarctic and Southern Ocean Research, University of Tasmania. Prior appointments included wintering in Antarctica conducting fast-ice research (1999/2000) and sea-ice modelling at the University of Alaska, Fairbanks. Her email is Petra.Heil@utas.edu.au.

Petra Heil

Steven Phipps recently commenced work as an earth systems modeller at CSIRO Marine and Atmospheric Research in Melbourne, Australia. Previously he worked at the Tasmanian Partnership for Advanced Computing in Hobart, Australia, and in 2006 he completed a PhD at the University of Tasmania in the field of earth systems modelling.

Steven Phipps



Nathan Bindoff

Nathan Bindoff is a physical oceanographer, specializing in ocean climate and the overall climate system. This expertise has been recognized by selection as a coordinating lead author for the ocean chapter in the Inter-Governmental Panel on Climate Change Fourth Assessment Report. In collaboration with others, he has developed new methods for analyzing and interpreting climate variability observations within the oceans, and has documented some of the first evidence for changes in the heat storage of Mode Waters, in the Indian, Pacific (North and South) and Southern Ocean.