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Toward a high-resolution coupled ocean-sea ice model

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ABSTRACT

This paper reports on the implementation of a novel numerical code of a coupled ocean-ice model using an existing ocean code and a revised sea-ice code. The numerical coupling is afforded by the *OASIS* coupler (CERFACS). All data exchange between the sub-models is strictly limited to the coupler. The coupler represents high-level processes with the sub-models being executed as directed by the coupler. Details of the model physics, their numerical implementation and setup as well as information on the coupling strategy are presented here.

Initial tests on the sub-models and the coupler configuration showed that both the ocean and the sea-ice model codes scale well with increasing number of CPUs. We also show that the overhead due to the explicit numerical coupler are small compared to the overall compute requirements of the sub-models.

INTRODUCTION

The Tasmanian Partnership for Advanced Computing [TPAC] is the national expertise centre for modelling of oceans and atmospheres. TPAC is engaged in several large-scale climate modelling projects, and collaborates with a large number of scientists in the Australian and overseas scientific communities. A lack of interactive ocean-ice models has been identified within the Australian scientific community. As a consequence, one of the main projects at TPAC is the delivery of a global coupled ocean-sea ice model, that is suitable for Antarctic and Southern Ocean research.

Scientific research into the sea ice and polar oceans are important to increase our understanding of the climate system, and to derive the knowledge required to build a numerical prediction system for sea-ice around Antarctica and how it will change from inter-annual to millennial timescales. Antarctic sea ice is an important component of the Southern Hemisphere climate. It provides a habitat for life (e.g., algae, mammals) and it also is a transport medium for freshwater and biological matter. Sea-ice forms a barrier between ocean and atmosphere and reduces the exchange of thermal energy, water vapour and gases between the two media. Sea ice, ocean and atmosphere interact with each other through many processes. E.g., the sea-ice albedo is much larger than the ocean's albedo, this has a large-scale effect on the net

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incoming solar radiation [Ebert et al., 1995] and consequently reduces the absorption of solar energy into the upper ocean. The thermodynamic growth of sea ice and the subsequent desalination of the ice gives rise to a transport of salt from the ice into the ocean, which increases the water density over the shelf, thereby driving the deep vertical overturning cell in the global ocean circulation. High ice-growth rates (e.g., in regions of polynyas) are generally concentrated in small areas of shallow water. These regions are often insufficiently resolved or even unresolved in coupled climate models. All this exemplifies that there is an urgent need for a sophisticated numerical framework of a coupled ocean-ice model for the application of Antarctic and Southern Ocean research.

MODEL DESCRIPTION

A summary description of the sub-models and the model physics is described in this section.

The ocean sub-model

The *standard* ocean sub-model used in this coupled ocean-ice code is the *Modular Ocean Model* [MOM] version 4. This model is not released yet, so work to date has been carried out using a β release of MOM 4 kindly supplied by Steven Griffies at Geophysical Fluid Dynamics Laboratory (GFDL/NOAA Department of Commerce) and is suitable for use in studies of the oceanic circulation at seasonal, inter-annual and climatic time scales. MOM 4 is a z-coordinate, primitive equation, ocean model with the generalised horizontal orthogonal coordinates discretised on a Arakawa B-grid [Griffies et al., 2002]. MOM 4 utilises MPI for parallelism and the computational domain is decomposed into latitude bands or latitude longitude tiles.

The sea-ice sub-model

Three main components form the sea-ice sub-model used here. These are the sea-ice dynamics, ice advection and the sea-ice thermodynamics. Within the sea-ice model the calculations to derive the ice dynamics are the most compute intense component. The viscous-plastic (VP) description [Hibler, 1979] uses an iterative numerical method, which does not parallelise well. To overcome this problem Hunke

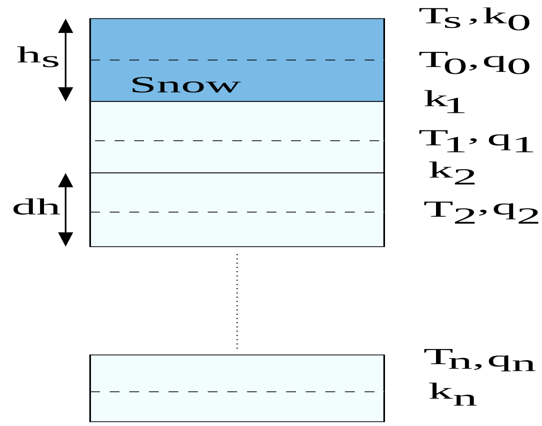

Figure 1: Vertical conduction of thermal energy through the sea ice and snow.

and Dukowicz [1997] have proposed an elastic-viscous-plastic model (EVP) with an explicit numerical scheme. They introduce an elastic component in the equation for the strain rate, so that the VP and EVP models are the identical under *steady state* conditions.

The transport equations are solved using an upstream advection scheme [Smolarkiewicz, 1984] with small implicit diffusion. This advection scheme is iterative. For an increasing number of tracers to be advected, solving the transport equations becomes more and more compute intense. To alleviate this problem an incremental remapping method [Hunke, 2001] has been proposed and is used.

Changes to the ice-thickness distribution arise from thermodynamic growth/decay and from mechanical redistribution. Changes in ice thickness due to thermodynamic processes are calculated following Heil et al. [1996] considering energy closure (Fig. 1). The mechanical redistribution scheme [Lipscomb, 2001] incorporates a redistribution scheme, a ridging function, an open-water opening/closing function, and a modification function. The redistribution scheme accounts for sea-ice area and volume that are reallocated over the various ice thickness classes. The ridging function tracks the surface ratio of ice destroyed by ridging in each category. The open-water function describes the overall change in sea-ice area from the strain rates in each grid cell. A modification function exists for the ice strength, which is proportional to the rate of change of the potential energy during ridging.

Following Lipscomb [2001] the sea-ice thickness is linearly remapped. This involves the conversion of thermodynamic ice-growth rates into thickness changes for each ice category, followed by the calculation of the ice-thickness distribution function based on the area and volume of sea ice displaced in each thickness category. Excess ice area and volume are remapped by integration of the thickness distribution function. The final step is readjustment of the ice thicknesses for each category to the original values.

The atmosphere sub-model

The current setup includes a data-based atmosphere model which can either supply data from the NCEP re-analysis projects (both re-analyses 1 and 2) via OASIS or calculate radiative and turbulent heat fluxes directly. In future developments this data sub-model can be replaced by an atmospheric General Circulation Model. For example, the inclusion of a polar version of the Fifth-generation Mesoscale Model (MM5) [Bromwich et al., 2001] would give forecasting capabilities to the coupled ocean-ice model.

COUPLING OF THE SUB-MODELS

The numerical coupling is provided by the *ocean-atmosphere general circulation model coupler* “Ocean Atmosphere Sea Ice Soil” (*OASIS*), which has been obtained from the Global Change and Climate Modelling Team at CERFACS (European Centre of Research and Advanced Training in Scientific Computation), France. *OASIS* has been employed for the coupling of ocean and atmosphere General Circulation Models [Guilyardi and Madec, 1997]. *OASIS* allows a modular design (Fig. 2). Multiple executables are used during run time. This is an important feature for the

Table 1: Overhead associated with the numerical coupler as a percent of total run time for coupled atmosphere and sea-ice model.

Overhead/field for data atm (%)	Overhead/field ice model (%)	Total overhead/field (%)	No. of fields
0.13	0.24	0.08	27

Overhead for data atm (%)	Overhead for ice model (%)	Total overhead (%)
2.03	4.82	1.65

coupled ocean-ice model, as the long-term aim is to provide the researchers with a choice of numerical codes for each of the sub-models in the coupled model. This will allow the researcher to evaluate the performance of one sub-component model over the other in respect to their scientific application.

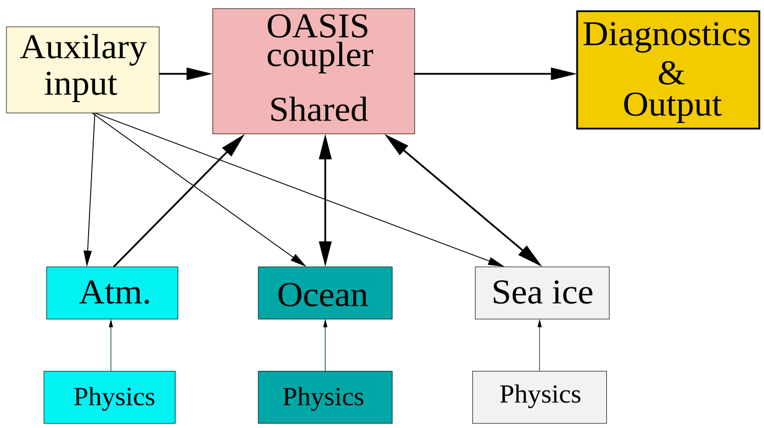

Figure 2: Sequence of numerical coupler for a three component ocean-ice model with data atmosphere.

OASIS gives flexibility to temporal and spatial resolutions used within the sub-models, while it synchronises the time evolution of the coupled model. Here we use the *OASIS* coupler to facilitate the exchange of fluxes across the interfaces between atmosphere and ocean, atmosphere and sea ice, and sea ice and ocean. Test runs with initial coupling of two sub-models (data atmosphere and sea ice) show that the increase in compute time due to the numerical coupler are small compared to the compute time required by the sub-models (Tab. 1).

In this coupled ocean-ice model fluxes and data fields are exchanged between three horizontal interfaces (Fig. 3). The data atmosphere model is connected to the upper layer of the sea-ice model as well as to the upper layer of the ocean model. Exchange between ocean model and atmosphere model takes place over all grid cells. If there is sea ice within an ocean grid cell, then the atmospheric data fields are used to derive fluxes for that part of the ice-covered grid cell that remains ice free. Under Antarctic conditions a certain area is rarely covered by 100 % sea ice, and typical concentrations are between 70 to 95 % during winter.

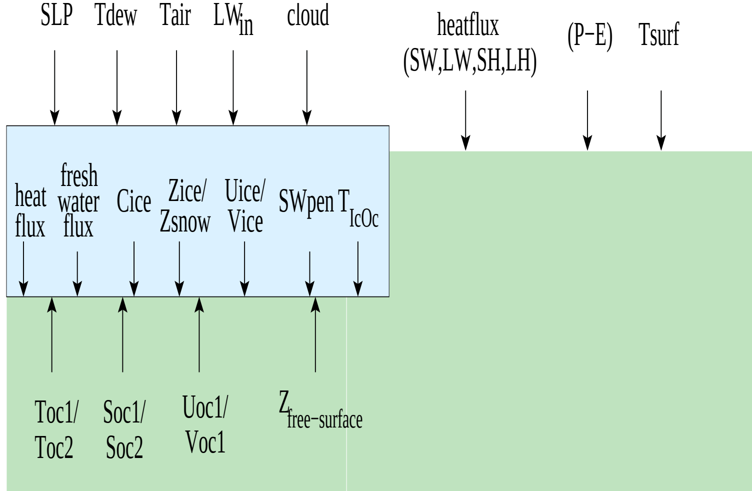

Figure 3: Fluxes across horizontal interfaces of the sub-models (atmosphere: white; sea ice: blue; ocean: green).

PARALLELISATION ISSUES

It is the aim of TPAC to provide researchers, on national basis, with an infrastructure and with numerical model codes that can be used on a range of computational platforms. This implies that the coupled model as such should scale well.

The performance of this coupled model is determined by several issues, which also affect its load balancing:

- horizontal grid resolution
- time-stepping
- physics included in the sub-models
- performance of floating-point operations
- ratio of memory access speed versus hardware specific communication latency

Using the *OASIS* coupler each sub-model runs as a separate executable with the communication between sub-model and coupler taking place at predetermined, regular intervals. The coupled model is synchronised at these communication points, and the CPU time spent by any sub-model between these synchronisations is used to optimize the load balance of the coupled system.

The communication with OASIS is both relatively infrequent (once every O(10) model time steps) and moderate in size, being two- dimensional fields. These features mean that the coupled system (relative to the individual models) is insensitive to both interconnect bandwidth and latency.

Therefore the major coupled performance issue, is selecting an appropriate number of CPU's for each sub-model, so that each sub-model reaches the communication synchronisation point virtually simultaneously.

OASIS is able to run sub-models over a heterogeneous system of computers, so that for example one sub-model could be running at a remote facility. While in general, the latency involved in such a configuration would be prohibitive, slowly evolving models (such as Antarctic ice sheet models with decadal to century timescales), have infrequent communication and would run efficiently.

Numerical setup: The ocean sub-model

MPI1 is used in MOM 4 for internal parallelism and the associated one or two dimensional domain decomposition. (Note the domain in never decomposed in the z-coordinate for efficiency reasons associated with the baroclinic wave mode). Scalability of the MOM 4β model on the APAC AlphaServer SC facility is shown in Figure 4, and is unsurprisingly dependent on the model resolution, with excellent scalability to 64 or more CPU's for a model resolution of $0.25° \times 0.25°$ or better.

Inter-model communication via OASIS is achieved using either MPI 2 on the TPAC SGI Origin 3400 or MPI 1 on the APAC AlphaServer SC.

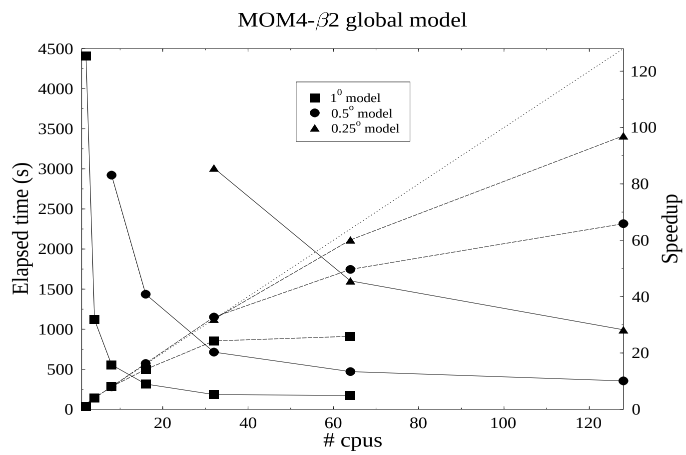

Figure 4: Parallelisation efficiency of MOM 4β on the APAC AlphaServer SC facility with two dimensional domain decomposition.

Numerical setup: The sea-ice sub-model

The sea-ice sub-model is written in Fortran90. MPI is used for the parallelisation of the sea-ice sub-model, and a two-dimensional grid decomposition with padding outside the sub-domain boundaries and periodic boundary conditions has been employed. The communication between the coupler and the sea-ice sub-model uses MPI2 on TPAC's SGI3400 and MPI1 on the cluster at the national facility.

The sea-ice model scales well with increasing number of processors. Tests carried out on an SGI3400 for a 1 week long run at a 10 minute external time step are shown in Figure 5. The dynamic computations (diamonds) are compute intense and contribute massively to the overall compute time (asterisk). The thermodynamic computations (star) and the ice advection part (crosses) take similar compute time and consume about one fifth each of the compute power required by the ice dynamics.

The model domain and grid

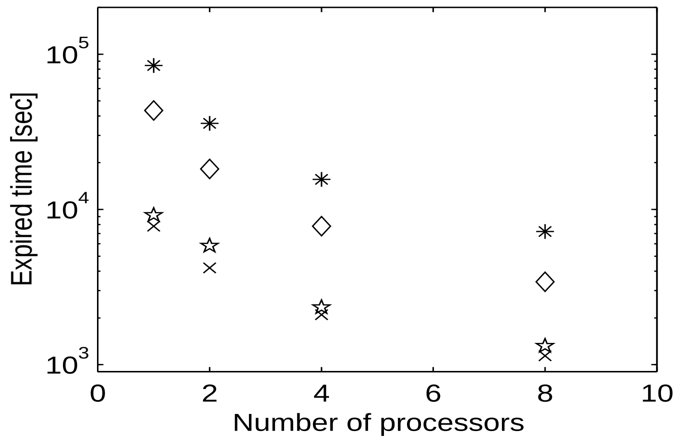

Figure 5: Execution time for the sea-ice sub-model and selected components when running on an SGI3400 with 1, 2, 4, and 8 processors. (See text for details.)

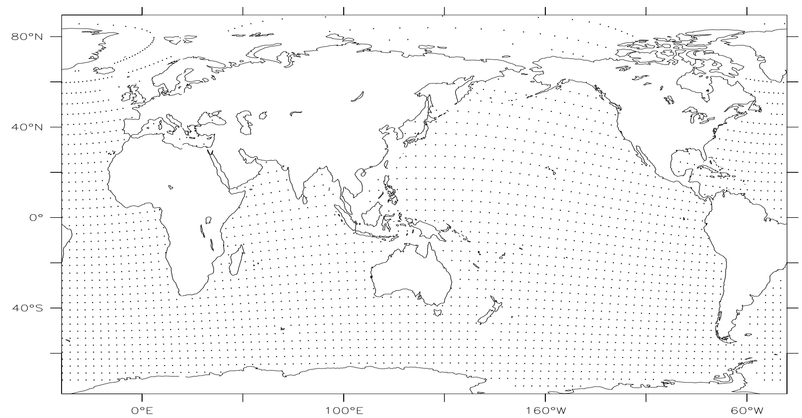

Figure 6: Displaced pole grid used for the ocean and sea-ice sub-models. Latitude and longitude lines are only shown every 1° .

A standard spherical coordinate latitude-longitude grid with its convergence of meridians generates two singularities (one at each pole), one within the ocean mask (the south pole is over land), which causes numerical instabilities and prohibitively small ocean time steps. To overcome this problem the singularities or poles of the ocean (or sea-ice) grid can be relocated over land using the conformal method of Bentsen et al, 1999. This model uses a displaced pole grid (Fig. 6) with the north pole at $320°E$ and $75°N$ (over Greenland) and with the south pole at the geographical south pole. The grid is irregular and distorted in both hemispheres but it is an everywhere orthogonal curvilinear grid, where the longitude lines intersect perpendicularly with latitude lines. It is a global grid and all grid cells with an ocean surface are included in the model domain.

The sea-ice sub-model uses the same model grid as the the ocean sub-model to ensure conservation of the parameters passed via the OASIS coupler. The sea-ice code uses the Arakawa-B grid [Mesinger and Arakawa, 1976] for spatial discretization.

GOALS

A coupled ocean-ice model is developed to gain the capability to predict on large spatial scales the behaviour of the ocean and the sea ice in response to changes in the atmospheric forcing. In order to resolve regions that are of important sources of modifications of the water-mass properties, the model domain has to have a high spatial resolution, both in the horizontal and also in the vertical.

By choosing a modular numerical coupler the current configuration of the coupled ocean-ice model can be used as a framework for future evaluation studies for sub-models. The *plug* & *play* approach will be valuable for when moving toward ocean-ice forecasting, where the atmospheric model component will continuously change as more data sources become available.

The modular approach available though OASIS allows for a flexibility not achievable with "fused" models. Sub-models can be interchanged for process type studies or sub-model comparisons. The interpolation built into OASIS allows for an easy change in grid resolution of sub components (for sensitivity experiments) without the need to recompile.

OUTLOOK

This is work in progress. At the time of writing, the ice and atmosphere sub-models had been both individually and jointly successfully coupled to OASIS. Preparatory work for the coupling of MOM 4 has been undertaken, and should be completed in the 2002-2003 financial year.

The availability of a variable resolution global coupled modular ice-ocean model will provide the Australian research community a valuable tool. It is envisaged that this model will be adopted as the next generation of the Australian Community Climate Model (ACOM). The flexible nature of the OASIS coupler will allow for the future inclusion of terrestrial and oceanic carbon cycle models and Antarctic ice sheet and ice shelf models.

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