# A Parallel Ocean Model for High Resolution Studies

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**Abstract.** Domain Decomposition Methods is used for the parallelization of the LODYC ocean general circulation model. The local dependencies problem is solved by using a pencil splitting and an overlapping strategy. Two different parallel solvers of the surface pressure gradient, a preconditioned conjugate gradient method and a Dual Schur Complement method, have been implemented. The code is now used for the high resolution study of the Atlantic circulation by the CLIPPER research project and is one of the components of the operational oceanography MERCATOR project.

## 1. Motivations

The study of the ocean and its influence on the global climate system require to know more precisely physical processes characterized by a broad range of spatial and temporal scales which encompass the relevant dynamics and involve longer integrations at finer resolution. One of the key to investigate a new physics is to design numerical models that can use state of art high performance computers. As computer technology advances into the age of massively parallel processors, the new generation of OGCM has to offer an efficient parallel tool to exploit memory and computing resources of distributed architectures. Developers need to adapt the software structure to benefit from these new generation of computers.

## 2. The OPA Model and Its Main Numerical Characteristics

The ocean is a fluid which can be described by the Navier-Stokes equations plus the following additional hypothesis: spherical Earth approximation; thin-shell approximation; turbulent closure hypothesis; Boussinesq hypothesis; hydrostatic hypothesis; incompressibility hypothesis. In oceanography, we refer to this set of

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equations as Primitive Equations (hereafter PE). A precise description of the different terms of PE and their parameterization in the OPA model are detailed in [1].

The ocean mesh is defined by the transformation that gives the geographical coordinates as a function of $(i, j, k)$. The arrangement of variables is based on the Arakawa-C grid. The model equations have been discretized using a centered second-order finite difference scheme. For the non-diffusive processes, the time stepping is achieved with a leapfrog scheme whose the computational noise is controlled with an Asselin time filter. For diffusive processes, an Euler forward scheme is used, but an Euler backward scheme can be used for vertical diffusive terms to overcome the strength of the vertical eddy coefficients.

With the second order finite difference approximation chosen, the surface pressure gradient contribution (SPG) has to satisfy a matrix equation of the form:

$$\mathbf{E}\,\mathbf{x} = \mathbf{b}\ , \tag{1}$$

where **E** is a positive-definite symmetric sparse matrix, and **x** and **b** are the vector representation of the time derivative of a volume transport streamfunction associated to SPG and of the vertical curl of the collected contribution of the Coriolis, hydrostatic pressure gradient, non linear and viscous terms of PE, respectively. The equation (1) is solved using a Preconditioned Conjugate Gradient (PCG) algorithm.

## 3. Parallelization Choices

The space dependencies associated with the resolution of the PE allows to identify that: computing SPG requires a knowledge over the whole horizontal domain, the vertical physics (thereafter VP that includes parameterization of convective processes, 1.5 vertical turbulent closure, time stepping on the vertical diffusion terms) involves each ocean water column as a whole, while for the remaining part of the model (hereafter PE') the computation remains local. The pencil splitting is an elegant solution to solve the dependencies problem of VP, to fit with the vertical boundary conditions of the ocean and preserve the parallel efficiency. The OPA finite-difference algorithms are solved using an Arakawa-C grid, so that the complication to specify the interface between neighbouring subdomains for the PE' leads to the easiest programming solution: a data substructuring with overlapping boundaries, the interface matching conditions are then related to usual Dirichlet boundary condition.

## 4. The Surface Pressure Gradient

In the PE model, the calculation of the SPG leads to a two dimensional horizontal problem that has to be solved with an iterative algorithm, either in time for subcycling time scheme [2], or in space for the other methods that all lead to an elliptic equation. One of the two algorithms used in OPA to solve the equation (1) is an adaptation to massively parallel computer of the diagonal PCG-algorithm. The parallelization of the PCG algorithm is rather straightforward. Indeed, since the preconditioner is a diagonal matrix, communication phases are only required in the calculation of a matrix-vector product and two dot products. The matrix vector product is computed using the same overlapping strategy as those used on PE' in order to solve the dependencies problem as an open Dirichlet boundary one. The local dot products are computed in parallel on each interior subdomain and sum over the whole domain through a reduction-diffusion operation to generate the coefficients associated with the two dot product. The ratio between computation and communication will therefore be a crucial point for SGP calculation and appear to stay strongly machine dependent. One looks for an algorithm [3] that minimizes the communication phase and/or the number of iterations in order to obtain good granularity tasks to benefit from massively parallel computers. The global domain $\Omega$ which boundary is $\partial\Omega$ is divided into a set of $N_p$ subdomains $(\Omega_p)_{p=1,N_p}$ which boundaries are $(\partial\Omega_p)_{p=1,N_p}$, and a non-overlapping interface between the subdomains:

$$\Gamma = \bigcup_{p=1,N_p} \partial\Omega_p - \partial\Omega \ .$$

For purpose of simplification the elliptic equation satisfied by SPG contribution [1, 4] is rewritten as (2a) with Dirichlet boundary conditions (2b):

$$E(x) = \nabla(\kappa \nabla(x)) = b \quad \text{on} \quad \Omega \ , \tag{2a}$$

$$x = x^{\partial\Omega} \quad \text{on} \quad \partial\Omega \ . \tag{2b}$$

Let us consider the set of the local second order elliptic operators $(E_p)_{p=1,N_p}$ associated to the SPG operator $E$ on $(\Omega_p)_{p=1,N_p}$, the Dirichlet-boundary problem satisfied by the global field $x$ associated to the source term $b$ (2) is equivalent, in its variational form, to the set of $N_p$ local problems with the continuity conditions, (3c) and (3d), on the interface $\Gamma$ :

$$E_p(x_p) = b_p \quad \text{on} \quad \Omega_p \ , \tag{3a}$$

$$x_p = x_p^{\partial\Omega} \quad \text{on} \quad \partial\Omega \cap \partial\Omega_p \ , \tag{3b}$$

$$x_p = x_{p_i} \quad \text{on} \quad \partial\Omega_p \cap \partial\Omega_{p_i} \ , \tag{3c}$$

$$\kappa_p \nabla(x_p) n_p + \kappa_{p_i} \nabla(x_{p_i}) n_{p_i} = 0 \ \ \text{on} \ \ \partial\Omega_p \cap \partial\Omega_{p_i} \ , \tag{3d}$$

where $x_p$, $b_p$, $\kappa_p$ and $x_p^{\partial\Omega}$ are the values of $x$, $b$, $\kappa$ and $x^{\partial\Omega}$ in the subdomain $\Omega_p$, $n_p$ is the outer normal vector of $\partial\Omega_p \cap \Gamma$. As $(\Omega_{p_i})_{i=1,N_a^p}$ is the set of the $N_a^p$ adjacent subdomains of $\Omega_p$, $x_{p_i}$ and $\kappa_{p_i}$ are the values of $x$ and $\kappa$ in the subdomain $\Omega_{p_i}$, $n_{p_i}$ is the outer normal vector of $\partial\Omega_{p_i} \cap \Gamma$. Let us introduce the Lagrange multiplier $\lambda$ associated to the continuity condition (3c):

$$\kappa_p \nabla(x_p) n_p = s\,\lambda \quad \text{on} \quad \Gamma \cap \partial\Omega_p , \tag{4}$$

where the factor $s = \pm 1$. The change of sign indicates that the outer normal derivatives of $x_p$ and $x_{p_i}$ are opposite each other.

The FETI methods consists in finding $\lambda$ the value of the normal fluxes along the interfaces $\Gamma$ for which the solution of the local boundary-value problems, (3a) and (3b), satisfies the matching condition (3c). Then, the global field $x$, whose restriction $x_p$ to each subdomain $\Omega_p$ is defined as the solution of the local Neumann problem, is continuous and also the normal fluxes. This is therefore the solution of the global problem. Mathematical proprieties, technical difficulties and a precise version of the FETI algorithm are detailed in [3].

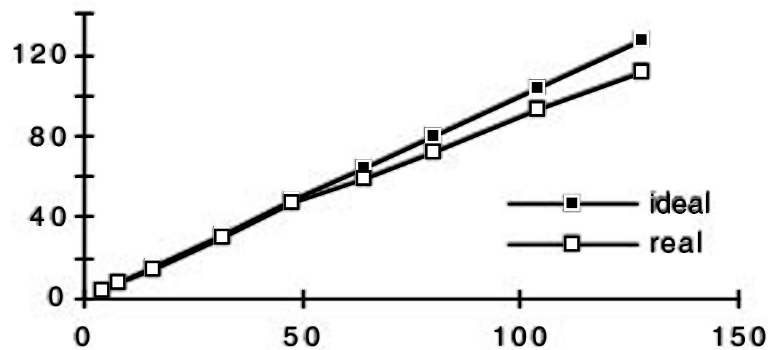


**Fig.1.** Speed up of the OPA code versus the number of subdomains for one hundred time steps integration on a Cray T3E system.

## 5. Conclusions

The ideas underlying domain decomposition methods have been integrated in the OPA model release 8. The portability of the code on multi-processors and mono-processor platform is preserved: the code has run on a large set of different platforms (Intel Paragon, Cray T3D, Cray T3E, IBM SP2, Fujitsu VPP) with different message passing communication libraries (NX, SHMEM, PVM, MPI). The straightforward parallelization of the conjugated gradient algorithm offers the advantage of an easy implementation. The FETI method exploits largest granularity computations and its numerical behaviour is more robust [3]. The speed up is nearly linear due to the halo effect when the number of subdomains increases and proves the total scalability [5]. It has been noticed that the initial code was quite well vectorized: a performance of 500 Mflops was obtained on a C90 processor whose peak performance is 1 Gflop. This code is interesting on massively parallel and vector machines: when tasks granularity is preserved it exploits the parallel efficiency of the domain decomposition implementation and/or the potential of the vector processors. A fully optimized version of the FETI algorithm is going to be evaluated in the context of large size computations [6]. Then the parallel model with the PCG algorithm [5] is confronted to the hardship of two major ocean experiments.

The CLIPPER project aims to obtain a High Resolution modelling of the ocean circulation in the Atlantic (1/6° at equator) forced by or coupled with the atmosphere. The program is aiming to model the oceanic circulation in the whole Atlantic Basin (from Iceland to Antartica) with the parallel OPA [7]. The basin extends to an area situated from 98.5° West to 30° East in longitude and from 75° North to 70° South in latitude. The grid size is 1/6° with 43 vertical levels and the resulting model mesh has 773*1296*43=43,077,744 grid points. The MERCATOR project aims to develop an eddy resolving global data assimilation system which has to become fully operational and has to contribute to the development of a climatic prediction system relying on a coupled ocean-atmosphere model [8]. The first objective is to represent the North Atlantic and the Mediterranean circulations with a 1/12° and a 1/16° grid size respectively and 42 vertical levels, the resulting model mesh has 1288*1022*42=55,286,112 grid points.

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