Development of Highly Parallel Ocean General Circulation Model using Cubic Grid System

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We are constructing a new ocean general circulation model (OGCM) in order to simulate long-term behavior of the ocean with eddy-resolving grid size. To do this, the OGCM have to be with high numerical and computational efficiency on the Earth Simulator. The development strategy of the OGCM is as follows. We construct a traditional OGCM with longitude-latitude grid and optimize it computationally on the Earth-simulator. Simultaneously, we employ cubic-grid system, which is a class of quasi-uniform grid systems on the sphere, to relax the stringent CFL condition, which arises in the longitude-latitude OGCMs with high resolution. Then we will combine those to realize the new OGCM on the Earth-Simulator. In FY2002, we have developed shallow water models on the cubic grid as the first step of the development of the OGCM. In the development stage, we derived an Arakawa-type momentum advection scheme. We also improved the computational performance of the longitude-latitude OGCM and achieved 13.8 Tflops with 3940 arithmetic processor on the Earth-simulator.

Keywords: Ocean General Circulation Model, Cubic Grid

1. Introduction

Earth simulator provides us unique opportunity of simulating the global ocean behavior with eddy resolving OGCMs. Such OGCMs will treat explicitly the effect of the meso-scale eddies, which play important roles in the climate system, so the OGCMs are expected to reduce the uncertainty of the climate modeling. However, OGCMs which already exist are not suitable for this purpose especially in the following two respects. One is that they are not necessarily suitable for the massively-parallel vector architecture so that they may not use the power of the Earth Simulator efficiently. The other is that they are constructed on the longitude-latitude grid system. In longitude-latitude models, time steps are restricted severely by the CFL criterion because of the convergence of the meridians around the poles.

We are trying to circumvent those deficiencies by employing a cubic-grid, which has quasi-homogeneous grid distribution on the sphere. Our development strategy is as follows. We develop an OGCM on a traditional longitude-latitude grid in order that we blush up our computational technique on the Earth simulator. Simultaneously we are developing and investigating an OGCM on a cubic grid. Then we will integrate both results to construct an efficient eddy-resolving OGCM on the Earth Simulator.

2. Cubic Grid

Cubic grids form a category of quasi-homogeneous spherical grids. Cubic grids are generated by mapping a grid on the cube to the sphere. Various mapping have already been suggested and we employed the method proposed by Purser and Rancic (1998). The advantages of this method are 1) uniform grid distribution, 2) structured grid so that it is relatively easier to employ existing schemes and 3) easier to vectorize and paralellize. The cubic grid has, on the other hand, the 8 singularities which correspond to the vertices of the original cube. We have to pay attention to the singularities because they may deteriorate the model performance. In this fiscal year, we tested the performance of this grid system especially focussing on the behavior of the singularities.

Fig. 1 Cubic Grid

In order to investigate the characteristics of the cubic grid, we first developed the shallow water model. As the set of governing equations, the vector invariant form on the curvilinear coordinate was employed. Arakawa B-grid was used to descritize the equations. On the way of the development, we derive Arakawa Jacobian on the entire cubic grid including the singularities. Arakawa Jacobian enables a momentum-advection scheme to conserve energy and also to conserve the enstrophy in non-divergent situation. These conservative natures prevent a type of nonlinear instability caused by anomalous energy cascade which is often seen in finite-difference schemes (Arakawa and Lamb 1977).

We subjected the scheme to the standard shallow water test suite (Williamson et al 1992). We also subjected the scheme which did not conserves energy and potential enstrophy for comparison. In the test, we did not apply any numerical viscosity. Fig. 2 shows the free-surface-height field of the simulation of Rossby-Haurwitz wave (test case 6 of Williamson's test suit). The resolutions of both models are about 3 deg. As can be seen, the height field of the model with energy and enstrophy conserving Arakawa-type scheme is much smoother than that of the other model. Addition to this, no apparent noise is generated from the singularity, which is shown as the three-forked line points on the figures. The development of the shallow water model is finished. We are planning to develop the three dimensional cubic grid OGCM in FY2003.

3. Highly Parallelized Longitude-Latitude model

Our longitude-latitude model is essentially the same to some other OGCMs which are widely used in climate simulation. The model employs the hydrostatic approximation. Arakawa B-grid is employed for the finite differencing. Z-coordinate is employed for the vertical direction. Explicit free surface method is used to solve separately the fast 2-dimensional barotropic wave so that the computing time is saved.

The two-dimensional parallel decomposition method is employed in this program. No parallel decomposition is done for the vertical. The parallelization is done using MPI library. The Earth Simulator consists of 640 nodes and each node consists of eight vector processors. For this computer architecture, using OpenMP in the node and MPI library between nodes would be suitable. However, there is no clear evidence that this hetero-structure parallelization is better than the parallelization done by using only MPI library. Therefore, in this program, the only MPI library is used for the parallelization.

In the barotropic equation solver, the ratio of the data communication time to the total elapse time is much larger than that of the baroclinic equation solver. When the data size becomes small, the communication time of parallel computers is determined by the latency time which does not depend on the size of the data and is not decreased when the size of the data is decreased. In the case of the Earth Simulator, the communication time is determined by the latency time when the data size becomes less than about 512KB.

In order to reduce the communication time, the data communication frequency should be reduced. The communication frequency can be reduced by sending several rows of boundary values of each domain to the neighbor's overlap

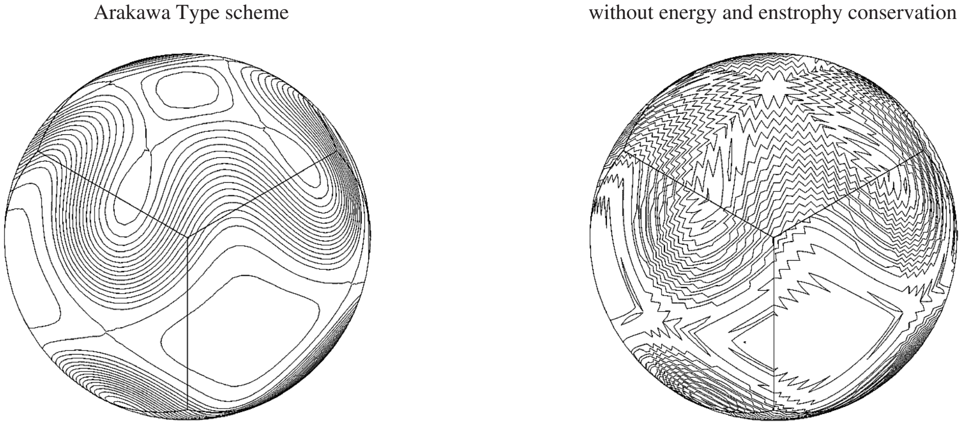

Fig. 2 Free surface height field of the Rossby-Haurwitz test case

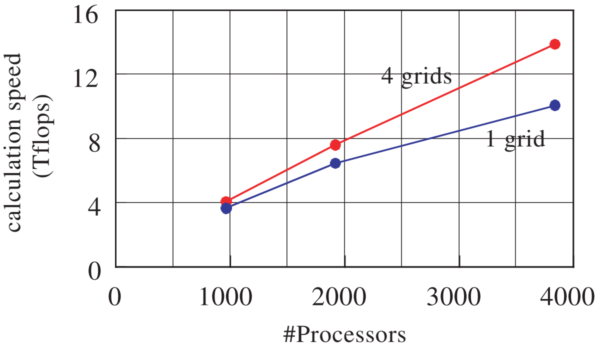

Fig. 3 Computational Performance with different width (1 grid and 4 grids) of the overlapping region.

regions and the time evolution of the values for several time steps are computed without communication in the overlap regions. Woodward was one of the first to apply this technique (Colella et al 1984). With these computational tuning, we achieved the computational speed of 13.9 Tflops with 3840 processors of the Earth Simulator. This speed is about 45 % of the peak performance of this number of processors.

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高並列化効率を有する立方体格子系海洋大循環モデルの開発

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地球フロンティア研究システムでは、渦を解像するグリッドサイズで全球を覆い、気候のシミュレーションを行うことが可能な、新しい海洋大循環モデル（OGCM）を開発中である。そのためには、現状のモデルよりも、地球シミュレータ上でよりよい計算効率を有することが必用である。新しい OGCM を開発するにあたり、まず、我々は、我々のグループで開発した緯度経度格子モデルを用いて、地球シミュレータ上で計算効率の改善を行う。次に、緯度経度格子系よりも時間ステップ幅が長くとれる立方体格子系を導入する。2002 年度、我々は立方体格子によるOGCM 開発の第一歩として浅水波モデルの開発を行った。その過程で、立方体格子上での Arakawa ヤコビアンを導き出し、エネルギーと、それに加え非発散条件下ではエンストロフィーを保存するスキームを見いだした。また、緯度経度格子モデルを用いて計算効率の改良を行い、3940 個のプロセッサを用いた計算で 13.8 Tflops を達成した。

キーワード：海洋大循環モデル、立方体格子