Dynamic Process for the Earth's Mantle

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The physical and chemical processes occurring in the Earth's interior are caused by heat transport from the within to the surface. This heat transport is mainly controlled by convective motion of mantle materials, and the convection generates density and temperature anomalies in the mantle. These anomalies can, in principle, be detected by observing anomalies in seismic wave speed. The aim of this study is to construct a new model of the global seismic velocity structure of the mantle and to simulate the 3D mantle convection numerically. By combining the seismic tomography model with the result of mantle convection simulation, we will propose a new model of global dynamics of the Earth's interior.

In this year, we installed the program for simulating the 3D mantle convection, the code name of which is 'TERRA', into the Earth Simulator. The installation was successfully done, the code was then optimized. The vector operation ratio and the efficiency of the parallelization were high enough to overcome the initial limitation for the node number usable in the Earth Simulator. As a result, the calculation of mantle convection became feasible to carry out with the Earth-like Rayleigh number, which is an order of magnitude larger than the value used in the conventional 3D simulation.

Keywords: Mantle Dynamics, Seismic Tomography, 3D Convection Simulation for the High Rayleigh Number

Report of the results

In this year, we installed the program for simulating the 3D mantle convection, the code name of which is 'TERRA', into the Earth Simulator. The TERRA code is a parallel program using the MPI communication routine among the cpus and had been originally developed on and highly optimized for the Cray vector XMP and YMP machines. Following the development of the superscalar architecture of the T3D/T3E Dec Alpha processors, the code has been optimized on these platforms. This code has already been succeeded in parallelization for 512 cpus with 49.1 Gflops on the Cray T3E-900.

The TERRA is a 3D spherical finite element code. It solves the equations for momentum and energy balance at infinite Prandtl number in a spherical shell, with given various equations of the state. The TERRA code can contain many complicated aspects which Earth's mantle convection has. In particular, the large spatial variations in the strength of silicate rocks that arise from the variations in temperature and stress can be treated, which will cause a remarkably Earth-like solution with plate-like surface movement, and an amount of toroidal mortion in the surface velocity field similar to that actually observed. Without using the Earth Simulator, the resolution so far achieved is as follows. The horizontal scale at the surface is about 60km with computational meshs having 65 layers, with about 160 thousands grid points for each, with a total of about 10 million grid points. The Rayleigh number should be 10 ~ 100 smaller than the real Earth value for this resolution.

The code was successfully installed into the Earth Simulator without any serious problems. To optimize the code on the Earth Simulator, we made alteration to the do-loops included in the code and vectorized it. Then we carried out the benchmark test for one of the main routines in the code and achieved the 60% peak performance. Next, to attain the parallelization ratio necessary for application to use more than 10 nodes, we improved the code and achieved more than about 99.96% of the ratio to obtain a temporary permission to use 64 nodes. The performance of the TERRA code was dramatically speeded up by using the Earth Simulator. The TERRA code exceeded the 1Tflops milestone with the 64 nodes on the Earth Simulator. The performance on the Earth Simulator is much faster than on the Cray T3E machines with the same number of the cpus. The results of the performance of the TERRA code by the Earth Simulator are shown in Table 1. When we use 64 nodes, it is possible to carry out the calculation with the computational meshs having 257 layers, with about 2.6 million grid points each for, with a total of about 0.7 billion grid points. It corresponds to the horizontal resolution at the surface of the Earth to be about 15km. The Rayleigh number can be set to about 10^8, which is close to the value of the real Earth. We carried out the calculation of the simple Rayleigh-Benard convection with 10^8 Rayleigh number, where internal heating, variable viscosity, yield strength and 670km phase transition are

Table 1 The performance of the TERRA code in billions of floating point operations per second (Gflops) on parallel Cray T3E systems and on the Earth Simulator.

Number of the processor	T3E-600	T3E-900	T3E-1200	Earth-Simulator
16				43
64	5.49	6.62	8.44	246
128	10.4	12.7	16.4	
256	22.1	26.2	32.3	587
512	42.5	49.1		

not included. The temperature fields resulted from the simulation are shown in Figures 1 and 2. These results indicate that the higher the Rayleigh number is, the smaller the flow structure becomes and the more turbulent flow occurs. These are consistent with the results by the laboratory experiments carried out with viscous fluid. Our next plan is to carry out the calculation of convection by using the Earth-like values for all the primary physical parameters and including the realistic silicate deformation law, internal heating, and phase boundaries. To simulate the mantle convection considering such many complicated aspects, the higher resolution is needed so that the TERRA code should be more optimized on the Earth Simulator with usage of more nodes. By the simulation under a setting very close to the real Earth, we hope to simulate the convection involving plate motions, hot plumes, and subducted slabs, as has been imaged from the seismic observations.

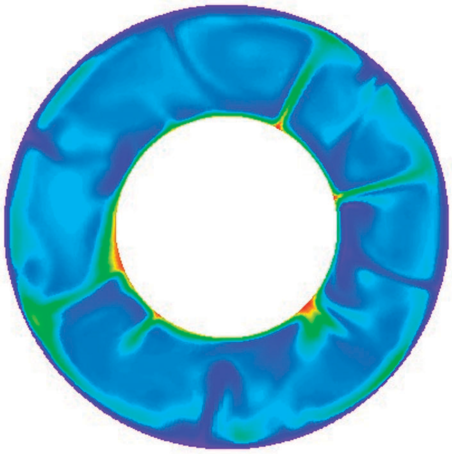

Fig. 1 The temperature field of the Rayleigh number = 10^6.

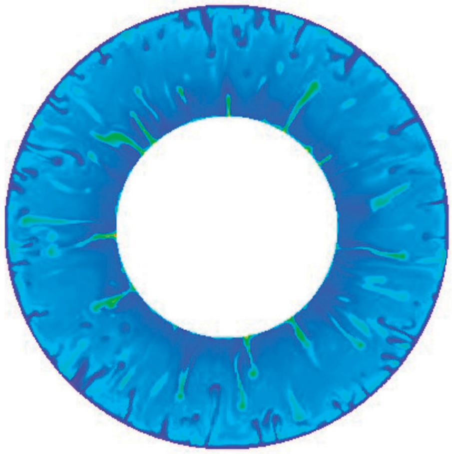

Fig. 2 The temperature field of the Rayleigh number = 10^8.

地球マントル変動の力学過程

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固体地球の変動は、地球内部の熱エネルギーの地表への流れによって支配されている。地球内部に生じる熱的非平衡状態はマントル内部に対流運動を生じさせ、この対流運動が、地球深部から外部への熱輸送の主要手段である。マントルの対流運動は、密度及び温度の異常パターンを引き起こし、それらは地震波速度異常の三次元構造として地震学的に観測可能である。地震波速度は、通過するマントル物質の温度によって変化する。よって速度異常分布から、マントル内部の温度、そして密度分布の情報を得ることが出来る。本研究課題では、地球内部で生じている様々な物理的化学的プロセスを解明する為に、地震観測のデータを統合してマントル内部の地震波速度構造モデルを構築することと、三次元マントル対流シミュレーションを行いマントル対流のモデル化を行うことである。この両者を組み合わせることにより、最終的には全地球マントル変動の力学過程を明らかにする。本年度は、まず初めとして地球シミュレータへの三次元マントル対流シミュレーション用プログラムの移植を行った。本コードはTERRAと呼ばれ、大規模対流数値実験用の汎用並列プログラムである。移植は問題無く完了し、またコードを改良することにより地球シミュレータへの最適化を行い、ベクトル化率、並列化率共に、地球シミュレータセンターが課した利用ノード数の制限の解除申請を行える値を得ることが出来た。本コードは64ノードの暫定利用許可を得ることが出来、結果、今迄の三次元マントル対流シミュレーションで利用されていたパラメータ（レイリー数）よりも一桁高い値の計算を実行出来るようになった。即ち、TERRAコードを地球シミュレータ上で実行することにより、現実的な地球の持つパラメータを用いたマントル対流の数値実験が世界で初めて可能となった。

キーワード：マントルダイナミクス、地震波トモグラフィ、高レイリー数対流の三次元数値実験