Numerical Simulation of the Mantle Convection

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A numerical simulation of mantle convection is the most powerful tool for the understanding of the dynamics and evolution of the Earth's mantle. To this goal, we optimized or newly developed the simulation codes which can handle various complexities relevant for the realistic mantle convection. These codes are utilized to study the effects of solid-state phase transitions and strongly variable viscosity on the convective planforms in the mantle, and to predict the motion of the surface plates on the Earth.

Keywords: mantle convection, plate motion, phase transitions, variable viscosity, spherical shell geometry

1. Introduction: Aim and Strategy

The Earth's mantle is the spherical shell composed of silicate rocks, and it ranges from approximately 5–50 km to 2900 km depth. Although the mantle behaves like an elastic solid on short time scales, it acts like a highly viscous fluid on long time scales. The mantle also acts as a heat engine, and it convects in order to mainly transport the heat from the hot interior to the cool surface. The convective motion in the mantle is observed as the motion of tectonic plates on the Earth's surface. The motion of surface plates in turn drives seismicity, volcanism and mountain building at the plate margins. Thus, the mantle convection is the origin of the geological and geophysical phenomena observed at the Earth's surface. A major tool for understanding the mantle convection is numerical analysis. It has been playing an important role in the study of mantle convection.

The ultimate goal of this project is to understand the processes which affect the dynamics and evolution of the Earth's mantle. To this goal, we aim at developing numerical models of mantle convection which are consistent with the observation results such as seismic tomography and geological evidence. The research of this project is divided in two subgroups, according to the nature of phenomena to be considered. First subgroup deals with time-dependent simulations of mantle convection, and aims at understanding the effects of various complexities on the dynamics and evolution of the Earth's mantle. Second subgroup deals with instantaneous flows in the mantle, and aims at understanding the nature of mantle convection by making good use of the observation results as their boundary conditions.

2. Simulations of Time-Dependent Convection in the Mantle

2.1. Effects of Endothermic Phase Transition on Convective Flow Patterns

T. Yanagisawa, Y. Yamagishi, D. Stegman and J. Baumgardner carry out simulations in a three-dimensional spherical geometry using the TERRA code[1], which is based on the finite element method using a structured mesh. This code was implemented and optimized for the ES through their efforts in FY2002. By using up to 128 processor nodes, it is capable of covering the entire mantle with the spatial resolution less than 30 km.

In FY2003, the TERRA code is utilized to study the effects of endothermic phase transition separating the upper and lower mantle on the convective flow patterns. An endothermic phase transition (with negative Clapeyron slope) is known to act as a "barrier" to flows penetrating across the phase boundary. Yanagisawa and others carried out systematic calculations varying the Rayleigh number *Ra* and the Clapeyron slope γ associated with the phase transition located at the 660km depth from the Earth's surface. They successfully reproduced the change in the flow patterns [2), 3), 4)] between (i) a double-layer convection where the convection separately occurs in the upper and lower mantle, (ii) a single-layer convection where the convection cells extend through the entire depth of the mantle, and (iii) an intermittent layered convection where a mass exchange (sometimes called by "avalanche" or "flushing event") occurs locally and intermittently between the upper and lower mantle. They also confirmed earlier findings[4), 5)] that the avalanche occurs at different spatial scales depending on γ. Figure 1 shows the flow patterns obtained for two different values of γ. Many small-scale avalanches occur at the phase boundary when the Clapeyron slope is mild (Figure 1a), while the large-scale avalanches are dominant when the slope is steep (Figure 1b).

By carrying out simulations using broader range of parameter values, Yanagisawa and others are currently studying the differences in spatial and temporal scales of the avalanches caused by the difference in γ.

2.2. Optimization of Simulation Code Based on Stabilized Finite Element Method

A. Suzuki develops a code based on the stabilized finite element method for the convection in 3-D spherical shell and Cartesian geometries. This code has been proved to give accurate results by mathematical properties of the finite element method[6)]. Even in the presence of strong variations in viscosity, the code can perform robust computation of the Stokes equations with primitive variables for incompressible fluids. In addition, it allows keeping the spatial resolution uniform in space, because an unstructured mesh division is used in Cartesian coordinate system. However, this code is very hard to vectorize because of the unstructured mesh division and resulting random memory access.

In FY2003, A. Suzuki is engaged in improving the vectorization efficiency of the code. By converting parallelized loops into vectorized ones, the computation performance of the code is successfully enhanced by a factor of 2 compared to the code developed in FY2002. The optimization resulted in the vector operation ratio of 99.86% and the calculation speed of 811MFLOPS using 1 CPU. This code is currently under the optimization for MPI parallelization, and is expected to yield much better performance using multi-node calculations.

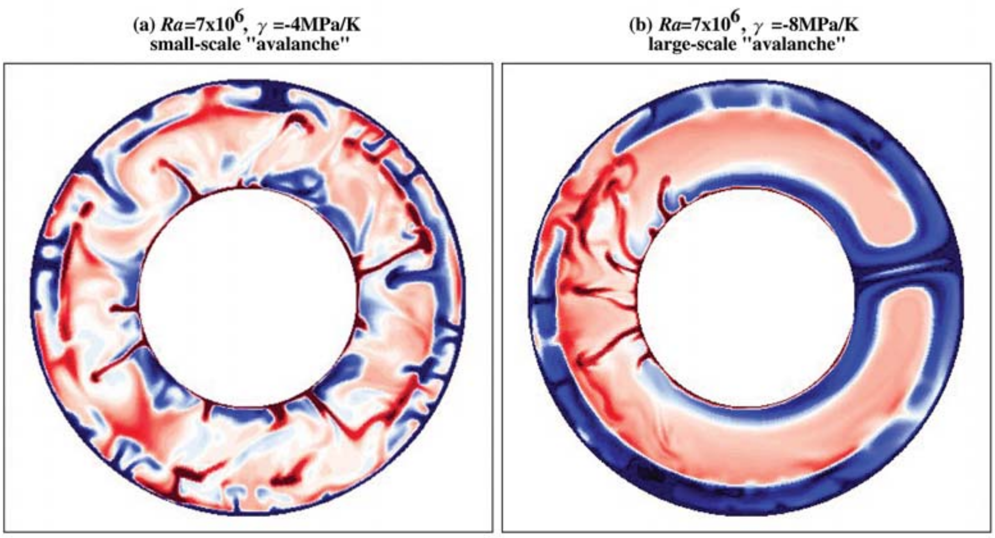

Fig. 1 Snapshots of the cross-section of temperature distributions obtained for two different values of the Clapeyron slope γ of the phase change between the upper and lower mantle. The model region is a spherical shell with outer and inner radii of 6400 km and 3500 km, respectively. The phase boundary is located at the depth of 660 km from the outer surface.

2.3. Development of New and Efficient Simulation Code for Mantle Convection

M. Kameyama develops a simulation code of convection in 3-D rectangular domain based on a new algorithm which came out through a close collaboration with the Solid Earth Simulation Group of the Earth Simulator Center. The details of the algorithm and simulation code can be found in Kameyama et al.[7]. This code is proved to be much more efficient than that developed through the activities in FY2002, even in the presence of strong variations in viscosity. It also shows sufficient vector and parallel performance for calculations with up to 15 processor nodes. By further utilizing this algorithm, it will be possible to conduct large-scale simulations under the conditions relevant for the Earth's mantle.

2.4. Simulations of Turbulent Mixing During Explosive Volcanic Eruptions

A numerical study of turbulent mixing during the volcanic eruptions is included in this project, as a potential extension of magma genesis. In the eruption clouds, the mixing with magmatic components (a mixture of volcanic gas and pyroclasts) and surrounding air is expected to occur in a turbulent manner. This turbulent mixing is considered to be very important to understand the dynamics of the eruption clouds. Y. Suzuki had developed a new technique for modeling the mixing of volcanic clouds and surrounding air, where the mixture is modeled as an ideal gas whose ratio of specific heat varies depending on the mass fraction of magmatic components.

In this study, Y. Suzuki also carried out three-dimensional simulations of turbulent mixing expected in the volcanic clouds. By conducting high-resolution simulations with 480 $\times$ 480 $\times$ 170 mesh divisions using up to 10 processor nodes, he successfully reproduced the three-dimensional behaviors of the eruption clouds.

3. Simulations of Instantaneous Convective Flows in the Mantle

3.1. Effects of One-Sided Subduction on the Plate Motion Modeling

S. Honda, M. Kido and Y. Iwase carry out simulations in a three-dimensional spherical geometry using their own code[8), 9)], which is based on the finite-volume discretization. Their code is designed to solve the instantaneous flow patterns for prescribed distributions of buoyancy and viscosity in the mantle.

Their study aims at reconciling the surface motion of the modeled mantle with the motion of the actual plates on the Earth. In particular, they focus on the effects of the "one-sided subduction", which is a unique feature of mantle convection of the Earth, on the modeling of present plate motion. They carry out preliminary calculations by varying the position of model slab (a portion of oceanic plate descending in the mantle) relative to the plate boundary as well as the viscosity of the lithosphere just above the slabs. They found that, under certain conditions, the flow pattern shows a feature indicative of one-sided subduction. In addition, the comparison between the cases with and without one-sided subduction suggests that the motion of the modeled plates agrees better with the observed motion for the case with one-sided subduction. Figure 2 shows the comparison in the surface motion between (a) the observation[10)] and (b) the result of one selected case accompanied by one-sided subduction. The directions of motion agree well in both cases. However, Figure 2 also shows systematic discrepancies in the magnitude of the plate velocity. For example, smaller plates in the models move faster than the observed one and vise versa.

Their preliminary results suggest a further consideration on the density and viscosity distributions of models might help improve the motion of the modeled plates. Honda and others are currently performing the systematic calculations with a broader range of parameter values.

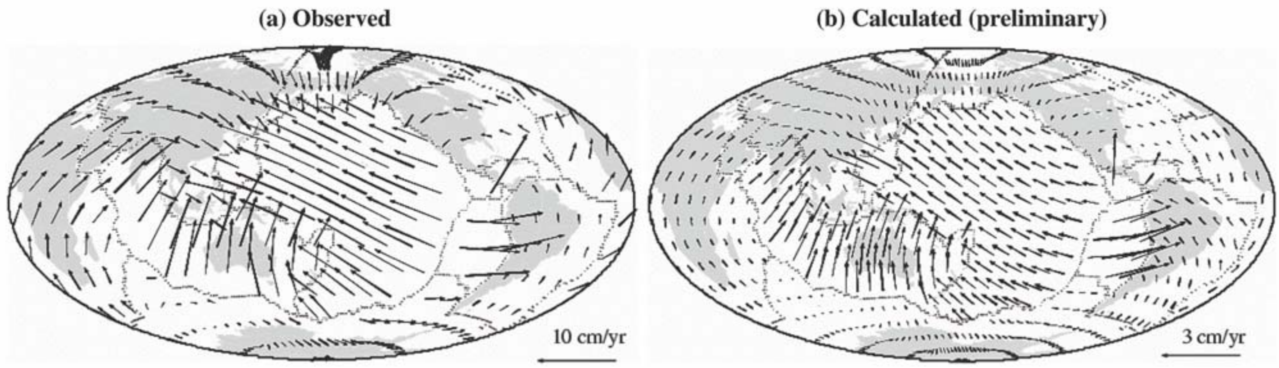

Fig. 2 Motion of surface plates. Shown in (a) is the observed velocity field[10)], while in (b) is an example of the calculated velocity field subtracted by the contribution from the rigid plate rotation.

References

1) J. R. Baumgardner, "Three-dimensional treatment of convective flow in the Earth's mantle", J. Stat. Phys., vol.39, pp.501–511, 1985.
2) U. R. Christensen and D. A. Yuen, "Layered convection induced by phase transitions", J. Geophys. Res., vol.90, pp.10291–10300, 1985.
3) P. Machetel and P. Weber, "Intermittent layered convection in a model mantle with an endothermic phase change at 670 km", Nature, vol.350, pp.55–57, 1991.
4) S. Honda, D. A. Yuen, S. Balachandar, and D. M. Reuteler, "Three-dimensional instabilities of mantle convection with multiple phase transitions", Science, vol.259, pp.1308–1311, 1993.
5) P. J. Tackley, D. J. Stevenson, G. A. Glatzmaier, and G. Schubert, "Effects of multiple phase transitions in a three-dimensional spherical model of convection in Earth's mantle", J. Geophys. Res., vol.99, pp.15877–15901, 1994.
6) M. Tabata and A. Suzuki, "Mathematical modeling and numerical simulation of Earth's mantle convection", in "Mathematical Modeling and Numerical Simulation in Continuum Mechanics", I. Babuska, P. G. Ciarlet and T. Miyoshi eds., vol.19 of "Lecture Notes in Computational Science and Engineering", pp.219–231, Springer, 2002.
7) M. Kameyama, A. Kageyama, and T. Sato, "Multigrid iterative algorithm using pseudo-compressibility for three-dimensional mantle convection with strongly variable viscosity", submitted to J. Comp. Phys., 2004.
8) Y. Iwase, "Three-dimensional infinite Prandtl number convection in a spherical shell with temperature-dependent viscosity", J. Geomag. Geoelect., vol.48, pp.1499–1514, 1996.
9) M. Yoshida, S. Honda, M. Kido, and Y. Iwase, "Numerical simulations for the prediction of the plate motions: Effects of lateral viscosity variations in the lithosphere", Earth Planet. Space, vol.53, pp.709–721, 2002.
10) D. F. Argus, and R. G. Gordon, "No-net-rotation model of current plate velocities incorporating plate motion model NUVEL-1", Geophys. Res. Lett., vol.18, pp.2039–2042, 1991.