Numerical Simulation of the Mantle Convection

Project Representative
Yoshio Fukao Institute for Research on Earth Evolution, Japan Agency for Marine-Earth Science and Technology

Authors
Yoshio Fukao *1, Tomoeki Nakakuki *2, Masanori Kameyama *3, Takatoshi Yanagisawa *1, Yasuko Yamagishi *1, Yujiro Suzuki *1, Atsushi Suzuki *4, Motoyuki Kido *5, Masaki Ogawa *6, Takao Eguchi *7, Yasuyuki Iwase *7, Takashi Nakagawa *8, Michio Tagawa *2, Millard F. Coffin *9, John Baumgardner *10, Mark Richards *11, Dave Stegman *12 and Stephan Labrosse *13

*1 Institute for Research on Earth Evolution, Japan Agency for Marine-Earth Science and Technology
*2 Department of Earth and Planetary Systems Science, Hiroshima University
*3 The Earth Simulator Center, Japan Agency for Marine-Earth Science and Technology
*4 Department of Mathematical Science, Kyushu University
*5 Research Center for Prediction of Earthquakes and Volcanic Eruptions, Tohoku University
*6 Graduate School of Arts and Sciences, University of Tokyo
*7 Department of Earth and Ocean Sciences, National Defense Academy
*8 Department of Earth and Planetary Science, University of Tokyo
*9 Ocean Research Institute, University of Tokyo
*10 Theoretical Division, Los Alamos National Laboratory
*11 Department of Earth and Planetary Science, University of California, Berkeley
*12 School of Mathematical Sciences, Monash University
*13 Institut de Physique du Globe de Paris

The dynamics and evolution of the Earth's mantle are considered to be influenced by several complexities of the physical processes. In order to understand the mantle convection in the Earth, a numerical simulation is a very effective tool. Therefore, we have been improving the models which take into account of such difficult aspects as the large variation of viscosity and the existence of phase transitions. On the other hand, models of the internal structure and evolution of the mantle have been proposed based on the seismological and geological observations. The seismic tomography reveals the large scale flow of mantle convection, while the geologic data suggest that the mode and activity of the mantle convection vary episodically. Our goal is to construct the models of the mantle convection which are consistent with these observational results. In this fiscal year, our effort was focused on the improvement of the model involving the phase transition around the 660 km depth. We discuss the implication for the dynamics and evolution of the Earth's mantle.

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

1. Introduction

The physical and chemical phenomena occurring on the surface and in the interior of the Earth are mainly controlled by the convective motion in the mantle. To understand these phenomena, we have to model the dynamics and evolution of the mantle convection. The convection is driven by the density and temperature anomalies in the mantle, which can be detected by seismic tomography as the anomalies in seismic wave speed. The seismic tomography images the pattern of the mantle convection having large spatial scales, which consists of two super plumes under the African continent and the South Pacific and the stagnant slabs on the seismic discontinuity around 660 km depth along the Circum Pacific. On the other hand, the temporal change of the vigor of mantle convection has been inferred from geological evidence. For example, in the middle Cretaceous, the spreading rate of seafloor was much higher than the present one, which indicates that the mantle convection at that time was much more vigorous as compared to that at present. By compiling these geological data, the activity of the mantle convection is expected to vary episodically. In addition, the Earth is the only planet on which the plate tectonics is observed. The plate motion is supposed to be an integral part of the mantle convection. To construct the realistic model of the Earth's mantle convection, the modeled convection should have large spatial scales, and reproduce the episodic behavior and the plate-like motion.

On the other hand, the mantle convection has many complex aspects, such as extremely large Prandtl number, high Rayleigh number, strong temperature dependence of viscosity, yield strength of materials, existence of phase transitions, and so on. The Earth's mantle convection must be affected by these complexities, and they entwine each other and complicate the structure and evolution of the mantle. Model construction of a realistic mantle convection needs to take into account of these factors, and clarify how they affect the mantle convection. Considering these various aspects, numerical simulation is the most suitable tool to investigate the mantle convection. In this project, we aim at developing numerical models of thermally-driven mantle convection, each of which includes strong temperature dependence of the viscosity, realistic rheology of the lithosphere, and the 660 km phase transition, respectively.

By using these numerical models, we discuss physics of the convection involving many complexities as existing in the Earth's mantle and seek for the possible mechanisms of large scale flow of the mantle convection, plate motions and the episodic activity of mantle convection. This study represents the first step of our goal of constructing the models of mantle convection which are consistent with the observational results such as seismic tomography and geological evidence.

2. The effect of the 660 km phase transition on the mantle convection

Here we describe the results of the numerical simulations of mantle convection in a three-dimensional spherical shell, which incorporates the 660 km endothermic phase transition. We use the TERRA code which is based on the finite element method. The details of this code are described in Baumgardner [1] and Bunge et al. [2]. We performed the simulations by using 32 nodes of the Earth Simulator. The spatial resolution is about 30 km on the Earth's surface. We carried out systematic calculations by varing Rayleigh number Ra, internal heating Rayleigh number RaH, and the value of the Clapeyron-slope at the 660 km depth dP/dT660 .

In Figure 1, various convection styles with different values of dP/dT_{660} are shown for Ra = 7×10^6. As can be seen, as the absolute value of the Clapeyron-slope $|dP/dT_{660}|$ increases, the pattern of the convection changes from the whole layer convection (for dP/dT_{660} = –2MPa/K) to two-layered one (for

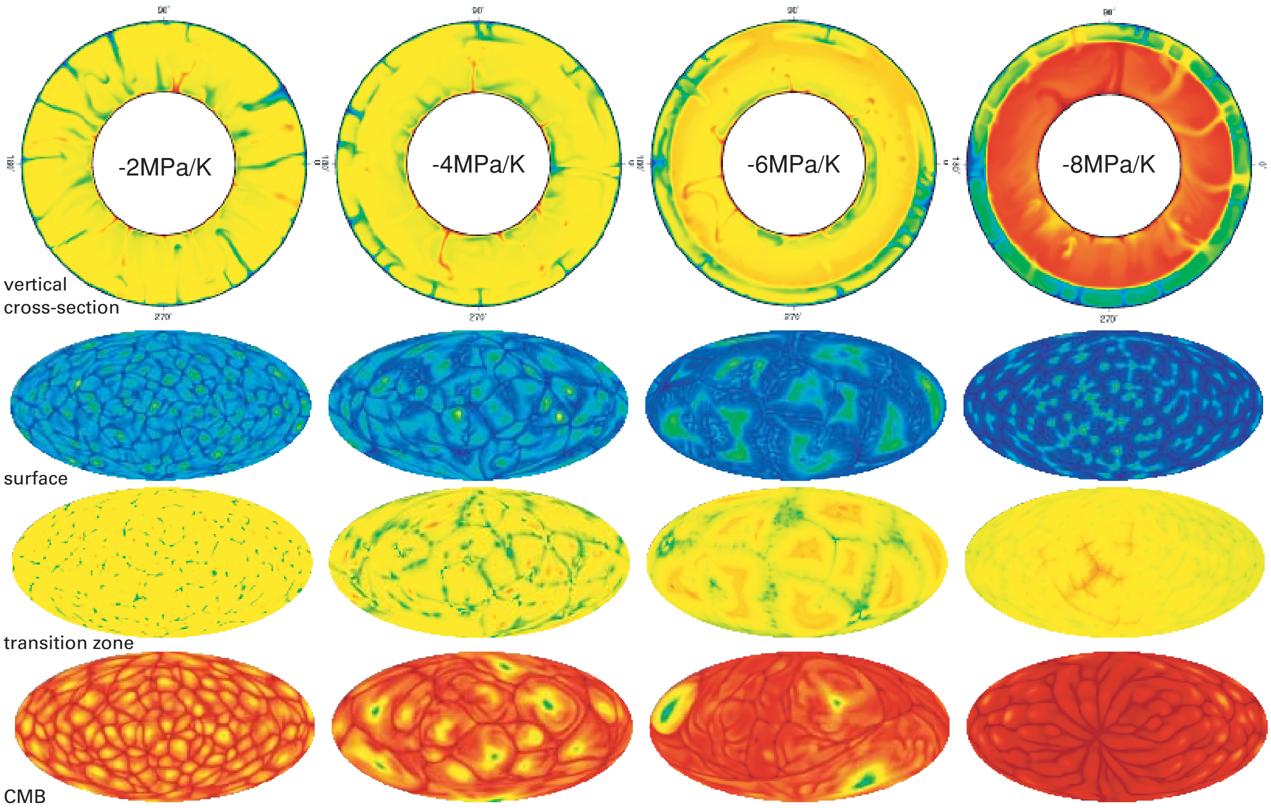


Fig. 1 Snapshots of temperature distribution obtained for four different values of dP/dT660. In these calculations, the Rayleigh numbers Ra and RaH are fixed to be 7×10^6 and 1.4×10^8, respectively. The top pannels show the distributions in longitudinal cross-sections, while the bottom three rows show the distributions at the top surface, the depth of 660 km, and the core-mantle boundary, respectively.

dP/dT_{660} = –8MPa/K). The cases with dP/dT_{660} = –4MPa/K and –6MPa/K belong to a transitional state between the whole layer convection and the two-layered one, where either of the two convective modes takes place alternatively and intermittently.

Figure 2 shows the regime diagram of the convection patterns summarizing the numerical results performed with various values of Ra and dP/dT_{660}. For the cases with Ra = 7×10^5 and 7×10^6, the convection style varies with dP/dT_{660}. When Ra is 7×10^4, in contrast, the convection shows a whole layer pattern regardless of the values of dP/dT_{660} employed here. As Ra increases, the transitional state between the convective regimes appears at smaller $|dP/dT_{660}|$. In other words, the convection tends to be separated at 660km depth for a large Rayleigh number, which is consistent with the previous studies [3]. Figure 2 also shows the ranges of dP/dT660 relevant to the Earth, estimated from the high-pressure experiments [4, 5]. Taken together with the estimates of the Rayleigh number under the Earth's conditions, Ra ≥ 10^7, the mantle convection of the Earth is most likely to belong to the intermittent regime.

In the intermittent convection, the intermittency is caused by the interaction between cold plumes and the phase transition. Because the endothermic phase transition acts as barrier for the convective flow, the cold plumes are accumulated on the boundary of phase transition. At this stage, the convection occurs almost separately in the upper and lower mantle. When the stagnant cold plumes become large enough to induce gravitational instability, they collapse down into the lower mantle catastrophically. This phenomenon is called

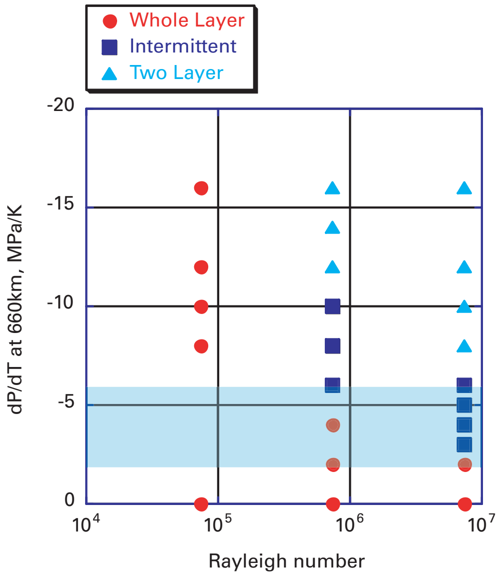
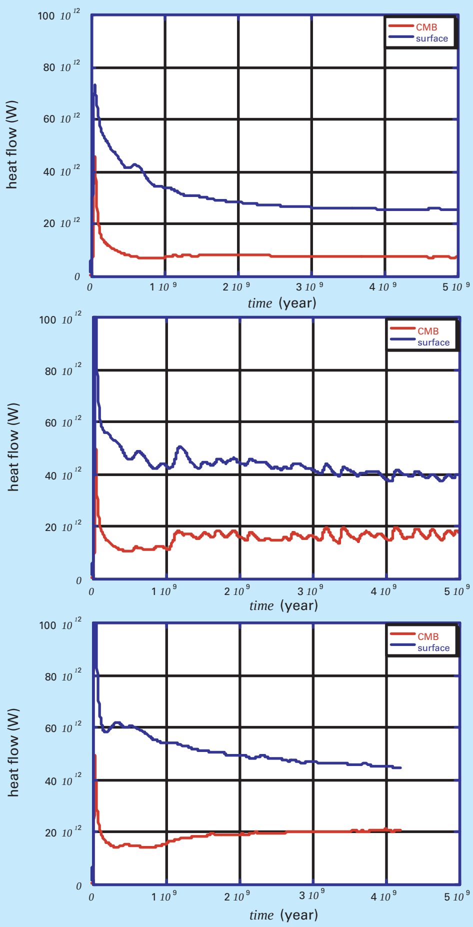


Fig. 2 A regime diagram of convective flow patterns in the plane of $|dP/dT_{660}|$ versus Ra. RaH is fixed to be 1.4×10^8. The shaded region indicates the range of dP/dT_{660} of the Earth estimated from the high-pressure experimental results.



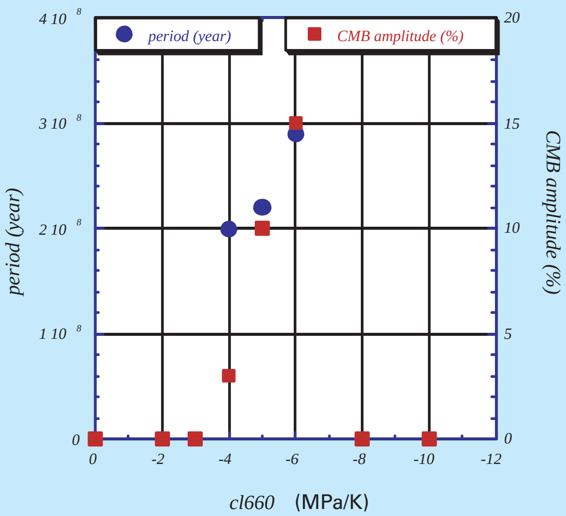


Fig. 3 (Left) Temporal change of heat flows from the surface and from the core mantle boundary. Shown in the top is the case of two-layered mantle convection, in the middle is the case of intermittent convection, and in the bottom is the case of whole layer convection. The Rayleigh number is 7×10^6, and the internal heating Rayleigh number is 1.4×10^8 in all the cases. (Right) Return period of temporal change of heat flow (blue circles) and the increase of heat flow from the core mantle boundary by avalanches at the stage of intermittent convection (red squares).

"avalanches" in the previous studies [6), 7)]. When avalanche occurs, the mass flux through the upper and lower mantle boundary becomes large and convection cells extend through the entire depth of the mantle. At the same time, the convective flows are reorganized into cells with large horizontal scales, which is consistent with global mantle models obtained by seismic tomography.

Also observed for the cases with the intermittent regime is a periodic variation of heat flow associated with the occurrence of avalanches (Figure 3). Heat flow rapidly increases when avalanches occur, and gradually decreases after the avalanches. Heat flow from the surface and that from the core-mantle boundary change synchronously and there is no time lag between them. For the case with Ra = 7×10^6, which is the maximum value in this study, and RaH = 1.4×10^8, avalanches increase the heat flow by a few to tens percent. The timescale of the temporal change of heat flow is several hundred millions years. Taken together with the geological evidence which implies a vigor of mantle convection in the mid Cretaceous, it is most likely that an avalanche occurred then. Figure 3 also shows that, as the absolute value of the Clapeyron-slope increases, the period of the temporal change is longer and the amplitude of heat flow variation is larger.

3. Achievements by other numerical modeling studies

In order to handle the strong temperature dependence of viscosity, we also develop numerical models for convection in 3-D spherical shell based on the stabilized finite element method. In FY2004, we successfully incorporated the effects of the phase transitions in the mantle transition zone into this numerical model. The distinctive point of this code is that it can give accurate results by mathematical properties of the finite element method [8)].

In addition, we are developing a two-dimensional numerical model of mantle convection together with the plate motion, and demonstrated that the model can reproduce the subducting motion of cold fluids similar to that of actual tectonic plates by considering realistic rheology of the lithosphere. For the next step, this model will be developed into the three-dimensional geometry.

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マントル対流の数値シミュレーション

プロジェクト責任者
深尾　良夫　　海洋研究開発機構　地球内部変動研究センター

著者
深尾　良夫[*1]，中久喜伴益[*2]，亀山　真典[*3]，柳澤　孝寿[*1]，山岸　保子[*1]，鈴木雄治郎[*1]，
鈴木　　厚[*4]，木戸　元之[*5]，小河　正基[*6]，江口　孝雄[*7]，岩瀬　康行[*7]，中川　貴司[*8]，
多川　道雄[*2]，Millard F. Coffin[*9]，John Baumgardner[*10]，Mark Richards[*11]，
Dave Stegman[*12]，Stephan Labrosse[*13]
＊1　海洋研究開発機構 地球内部変動研究センター
＊2　広島大学大学院 理学研究科
＊3　海洋研究開発機構 地球シミュレーターセンター
＊4　九州大学 数理学研究院
＊5　東北大学 地震・噴火予知研究観測センター
＊6　東京大学大学院 総合文化研究科
＊7　防衛大学校 応用科学群地球海洋学科
＊8　東京大学大学院 理学系研究科
＊9　東京大学 海洋研究所
＊10 ロスアラモス国立研究所
＊11 カリフォルニア大学バークレー校
＊12 モナッシュ大学 数理科学研究科
＊13 パリ大学 地球物理研究科

地球内部及び表層で起きている現象を理解する為には、地球のマントル対流の構造、およびそのダイナミクスの理解が必要である。マントル対流は一般的なレイリーベナール対流と異なり、粘性率の強い温度圧力依存性、内部発熱源、複数の相境界、および構成物質の降伏応力等の存在など、様々な複雑性を持つ。よって、マントル対流の物理モデルの構築には、これらの要素を考慮することが重要である。また一方で、マントル対流の構造は地震波観測などにより明らかになりつつあり、そしてその進化は地質学的な証拠から検証可能である。よって本プログラムでは、前述のような様々な物理要素を考慮したマントル対流の数値シミュレーションを行い、各々が対流に与える影響およびその物理を明らかにするとともに、観測事実と無矛盾なマントルモデルを構築することを目的とする。特に本年度は、地表から深さ660 kmに存在する相境界を考慮した三次元球殻のマントル対流の数値実験を中心的に実施した。その結果、地球マントルに近い条件下では、
1）660 km相境界に下降流が塞き止められ滞留し、上部マントルと下部マントルで流れ場が分断される。
2）滞留した下降流が重力的に不安定となり、やがて下部マントルに向かって一気に崩落する。この時マントルは全層にわたり攪拌される。
という状態を周期的に繰り返すことがわかった。特に相境界に滞留した下降流が崩落する際に、熱輸送量は急激に増加し、かつ対流運動の組織化が起き、巨大な流れが発生することが明らかとなった。このことは、地震波トモグラフィーが明らかにした、マントル対流の巨大セルの存在、および白亜紀時代に火山活動が活発化し、洪水玄武岩が形成されたことと矛盾しない。さらに他の数値モデルでは、粘性の強い温度依存性を組み込んだマントル対流計算コードにも、本相境界を取り入れることが可能となった。加えて、二次元において、リソスフェアのレオロジーを組み込むことによりプレートの沈み込みを再現できるようになり、現在三次元への拡張を行っている。

キーワード：マントル対流，相境界，粘性変化，プレート運動，三次元球殻