Simulation Study on the Dynamics of the Mantle and Core in Earth-like Conditions

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Thermal convection in the outer core and the mantle is the origins of various Earth's activities and essentially important in the Earth's evolution. We investigate the core convection using low-viscosity geodynamo models. A physical interpretation is given for different behaviors of two geodynamo models: a uniform-surface-temperature model and a uniform-heat-flux model. The thermal boundary condition for the core surface temperature regulates the thermal wind and generation of the toroidal magnetic field. The geomagnetic westward drift and torsional oscillations are simulated to understand mechanisms of short-term geomagnetic field variations. In the mantle convection, we use a three-dimensional spherical-shell code that includes effects of phase transitions, temperature-dependent viscosity with plastic yielding near the surface, and viscosity increase in the lower mantle, and find that, with realistic Rayleigh numbers, these three effects cause plate-like behaviors and slab stagnation and penetration around the transition zone.

Keywords: mantle convection, core convection, geodynamo, geomagnetic secular variation, slab stagnation

1. Introduction

Our group is composed of three subgroups, aiming for comprehensive understanding of the dynamics of the Earth's mantle and core as a combined solid-Earth system. The geodynamo group simulates thermal convection of the fluid outer core and a resultant generation process of the geomagnetic field. In order to reach the core conditions, we have made attempts to reduce viscous effects in the dynamo model by decreasing the Ekman number ($E = \nu/2\Omega c^2$; ν: kinematic viscosity, Ω: Earth's angular velocity, c: core radius) and the magnetic Prandtl number ($Pm = \nu/\eta$; η: magnetic diffusivity). The mantle convection group focuses on dynamical behaviors of the Earth's mantle and simulates infinite-Prandtl-number thermal convection. Particular attention has been paid on integrating realistic mantle properties (e.g., variable viscosity, phase transition, plate behaviors) into the model and reproducing the images obtained from seismic tomography. The geomagnetism and geoelectricity group aims to model electromagnetic properties of the Earth by comparison of simulated and observed data. Here we report some results of the geodynamo and mantle convection groups.

2. Geodynamo simulations

2.1 Impact of the boundary condition for the core-surface temperature

We have shown that, in low-viscosity geodynamo models of $E = 5 \times 10^{-7}$ and $Pm = 0.2$, which are one of the lowest-viscosity models, the solutions are dramatically different between a case where the core-surface temperature is laterally uniform and a case where the heat flux is laterally uniform at the core surface [1,2]. The uniform-surface-temperature model (USTM) produces sheet-like, high-wavenumber convection and a comparatively weak magnetic field that is almost stationary in time. The uniform-heat-flux model (UHFM) allows a large-scale convection pattern and a strong magnetic field that, driven by a zonal flow, moves retrograde like the geomagnetic westward drift. As the mantle convection is too slow to homogenize the core-surface temperature in the core's convective timescale, the USTM is geophysically unrealistic. The numerical results indicate that the USTM is not only theoretically inappropriate but fails to reproduce geomagnetic field behaviors. Other low-viscosity USTMs [3,4] resemble our USTM, but previous higher-viscosity USTMs [5] seem to have characteristics similar

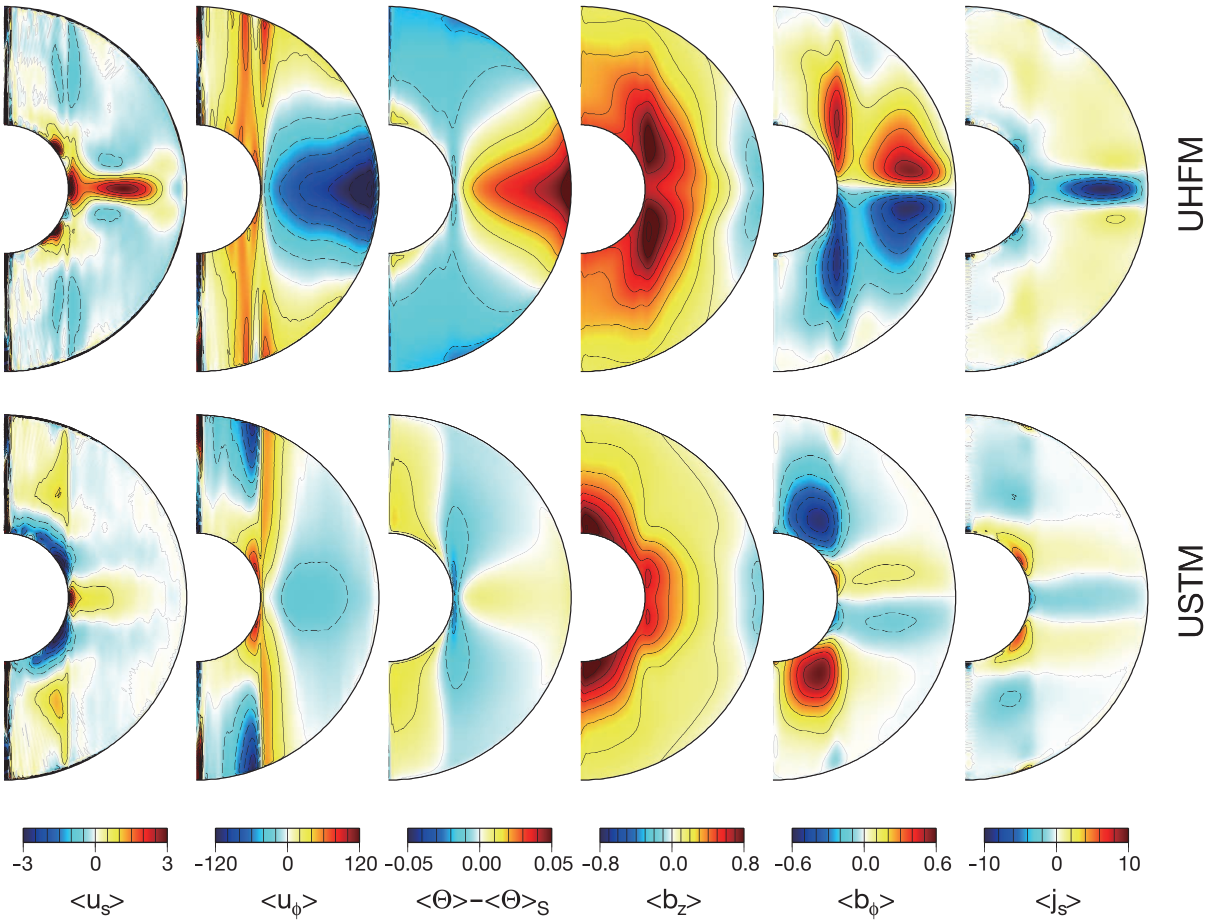

Fig. 1 The time-averaged axisymmetric structures of the solutions of the UHFM (top) and the USTM (bottom). Shown from left to right are the cylindrically radial and azimuthal velocities, the spherically asymmetric part of the temperature, the axial and azimuthal magnetic fields, and the radial electric current density.

to our UHFM, implying that the thermal boundary condition has a great impact only when the viscosity is low enough.

When averaged in time and longitude, the temperature perturbation, $\langle\Theta\rangle$, is a solution of the heat conduction equation with the source term, $C(r, \theta) = - \langle u_r \rangle \, dT_c/dr - \langle \boldsymbol{u} \, , \mathrm{grad}(\Theta) \rangle$, where T_c is the reference temperature, $\boldsymbol{u}$ is the flow velocity and $\langle\rangle$ denotes the time and azimuthal average. Even when $C(r, \theta)$ is the same, the amplitude of $\langle\Theta\rangle$ strongly depends on the boundary condition, because this elliptic boundary-value problem is intrinsically sensitive to the choice between the Dirichlet-type (USTM) and the Neumann-type (UHFM) boundary conditions. Suppose that initially there is a radial upwelling flow, $\langle u_r \rangle$, along the equatorial plane and that the nonlinear terms are negligibly small. The flow creates a positive $C(r, \theta)$ to heat up the equatorial region. We have confirmed that, when a simple flow distribution is assumed, the UHFM produces $\langle\Theta\rangle$ several times greater than the USTM in which the temperature variation along latitude is exactly zero at the surface. The greater $\langle\Theta\rangle$ in the UHFM produces a stronger azimuthal thermal wind and a stronger toroidal field because of the omega-effect. The resultant stronger Lorentz force in the UHFM, which is eastward to decelerate the thermal wind, requires a stronger radial upwelling flow, $\langle u_r \rangle$, at the equatorial plane because the major counter force to the Lorentz force is only the Coriolis force. Therefore, the initially imposed radial flow can grow by generating a strong toroidal magnetic field in the UHFM. This positive feedback makes the difference between the two models bigger and bigger until the nonlinear term cancels the heat source term $C(r, \theta)$. The USTM is less effective to drive a thermal wind, so the toroidal magnetic field cannot grow outside the tangent cylinder. These scenarios well describe the time-averaged axisymmetric structures of the two solutions (Fig. 1) and explain why the USTM became a weak-field dynamo [6].

2.2 Magnetic field changes of short timescales

The geomagnetic field changes in various timescales. As observational geomagnetic data during the past several hundreds years are relatively abundant, there is a possibility to make a detailed comparison between the model and such short-term data and obtain some information about the deep Earth. One of the most notable short-term geomagnetic field changes is the westward drift, whose phase velocity is estimated to be up to about 17 km/yr at the core surface and the signal is concentrated in a narrow equatorial belt [7]. In order to see such a short-timescale phenomenon, we performed geodynamo simulations

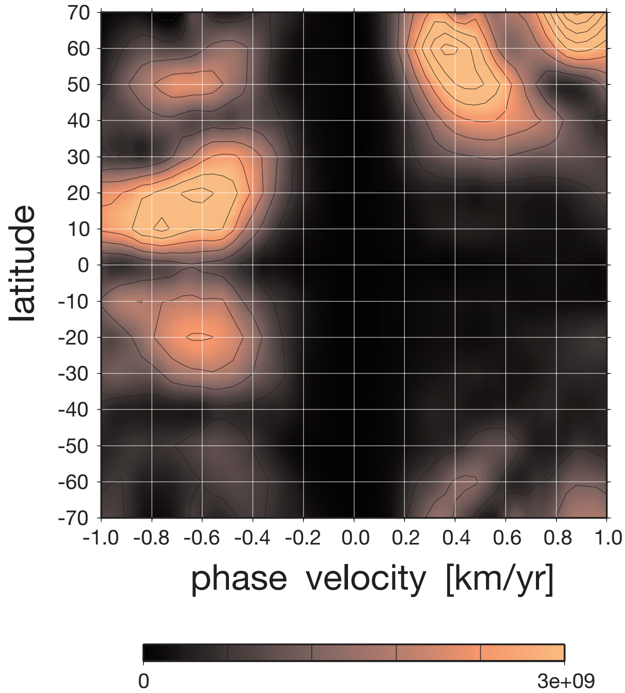

Fig. 2 The signal power of the radial component of the core-surface magnetic field moving in the azimuthal direction is plotted as a function of the phase velocity (a positive value means eastward propagation) and the latitude, obtained from the UHFM with $E = 2.5 \times 10^{-7}$, $Pm = 0.2$, $Ra = \alpha\beta g c^2/2\Omega\eta = 6400$ (α: thermal expansivity, β: temperature gradient at the core surface, *g*: acceleration due to gravity at the core surface).

using the UHFM and decreasing the Ekman number to 2.5×10^{-7}. We used a spectral method with the maximum spherical harmonic degree of 359. We plotted the core-surface field as a function of time and longitude at various latitudes and made a wave analysis in the ϕ -*t* plane to obtain the phase velocity of the strongest signal. The result indicates that the field propagation is most evident within the latitudes of +/- 30 degrees similar to the geomagnetic data (Fig. 2). The phase velocity can be converted to a dimensional value of 0.7 km/yr, if $\eta = 3$ m^2/s. There are some signals in the high latitudes that are both eastward and westward. The simulated westward drift is too slow to account for the observational data, implying that the Rayleigh number (Ra = 6400 in this case) should be much higher to drive a stronger thermal wind.

Another interesting short-term geomagnetic variation is caused by the torsional oscillations of the Earth's core. Provided that viscous and inertial forces are neglected, the integral of the azimuthal component of the Lorentz force over an axial cylindrical surface has to be zero (the Taylor's constraint). The angular velocity of the cylinder's rotation obeys a wave equation with some assumption, whose phase velocity is proportional to the root-mean-square magnetic field perpendicular to the cylindrical surface. It has been argued that the torsional waves cause decadal geomagnetic field variations that could be related to the change of the angular momentum of the mantle [8]. Figure 3 shows the time derivative of the zonal velocity averaged over an axial cylindrical surface of radius *s*. We made a wave analysis in the *s*-*t* plane to obtain the phase velocity, similar to the case of the westward drift. The result shows that the ingoing waves (toward the *z* axis) are more evident outside the tangent cylinder and the outgoing waves are seen near the equator, implying that the waves are excited around $s = 0.75$ and propagated to both directions, but they are absorbed at both ends of the tangent cylinder (Fig. 4). The phase velocity is slightly slower than the theoretical estimate, which may imply that a modification is needed to the theory of the torsional waves.

2.3 Improvement of geodynamo models

We made efforts to improve the numerical method and the model equations. We employ either the Chebyshev spectral or the finite difference methods to resolve the radial convective structure. In general, the former is more accurate with the same

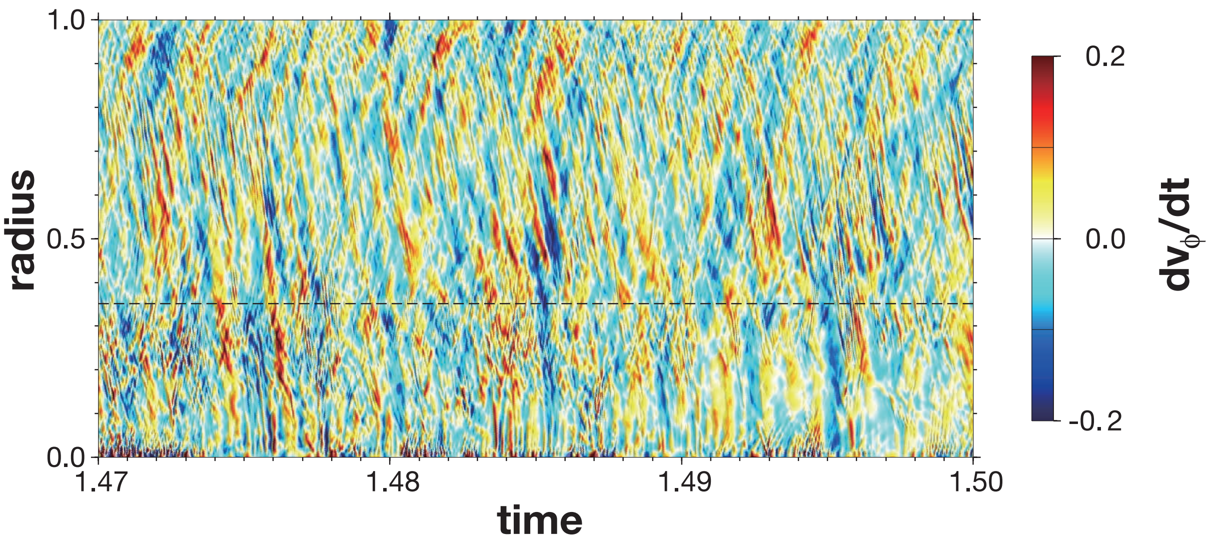

Fig. 3 The surface average of the time derivative of the azimuthal velocity as a function of the time and the cylinder's radius.

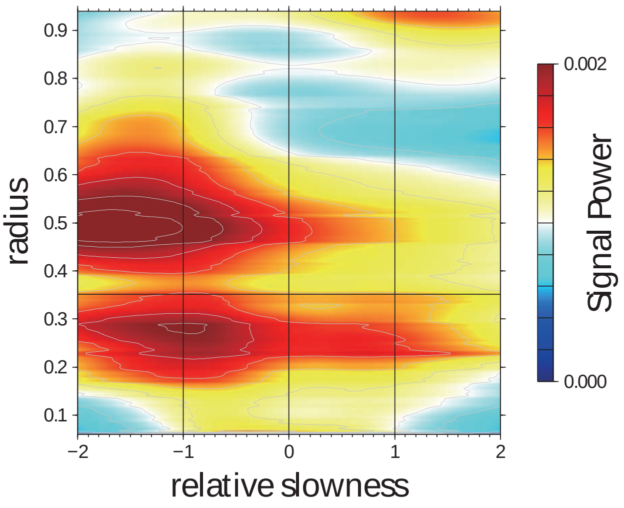

Fig. 4 The result of a wave analysis of the data shown in Fig. 3. The signal power is plotted as a function of the radius and the slowness that is normalized by the theoretically predicted slowness of the torsional wave.

degree of freedom (spectral modes or grid points), but the latter could be superior in computational speed. We modified the finite difference method by using the combined compact difference scheme [9] to cope with speed and accuracy. Preliminary calculations of the dynamo benchmark test show that the solution has 4th-order accuracy and the numerical integration is stable. We so far used the Boussinesq approximation for the core convection, which might be however inappropriate because of finite compressibility of the core fluid. We attempted to modify the Boussinesq equations using the incompressible approach proposed by Anufriev and Hejda [10]. We introduced the dissipation number and the ratio of the adiabatic heat flow to the actual heat flow at the core surface. By changing these numbers, we succeeded in simulating a thermally stable layer at the top of the core.

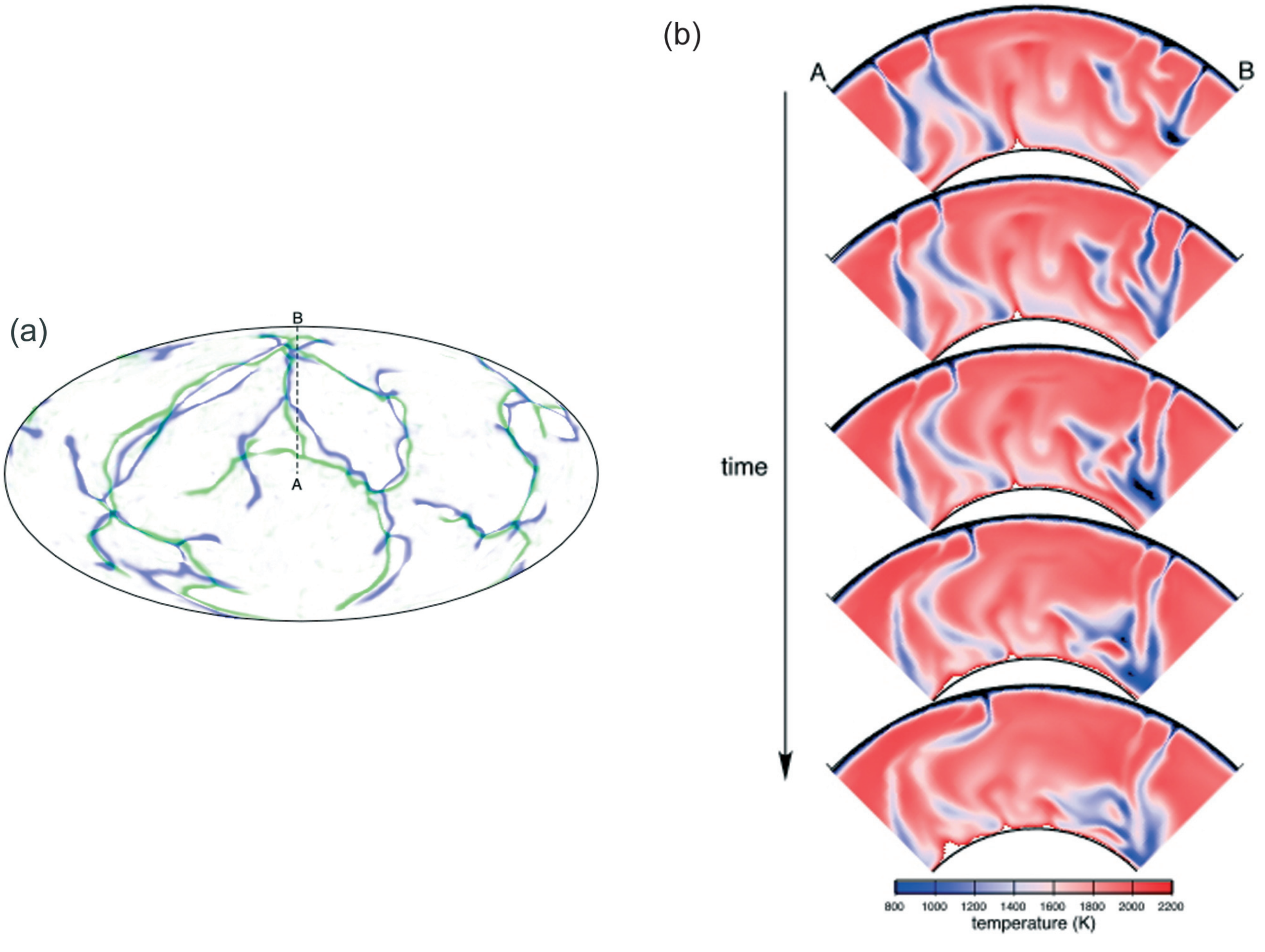

Fig. 5 Movement of the positions of convergence regions at the surface between 200 million years (a), and variation of the convection pattern in a vertical cross section (b). Rayleigh number is 2×10^7. Temperature dependency of viscosity with plastic yielding and phase transitions at 410 km and 660 km depth are included. Viscosity of the lower mantle is 40 times higher than the upper mantle. In (a), green: original positions of convergence regions (corresponding to the first frame in (b)), blue: 200 million years later (corresponding to the last frame in (b)). The broken line with A and B indicates the position of the vertical cross section in (b). In (b), temperature is shown by color-scale and the time interval for each frame is 50 million years. Stagnation of the subducted slab around the transition zone occurs with the horizontal migration of the downwelling flow in the upper mantle.

3. Simulations of mantle convection

The Earth's mantle is composed of solid rocks but it flows like a viscous fluid in a geologic time scale. This convective flow of the mantle is emerging as the motion of tectonic plates on the Earth's surface. The motion of surface plates causes earthquake, volcanism and mountain building at the plate margins. And as the mantle flow transports the heat from the hot interior, the whole of the Earth has been cooling through its history. It also controls the boundary conditions of the outer core. Hence, mantle convection is the key process for understanding the activity and evolution of our planet. Seismic tomography reveals the natural mode of convection in the Earth is whole mantle with subducted plates (slabs) clearly seen as continuous features into the lower mantle. Simultaneously existing alongside these deep slabs are stagnant slabs which are, if only temporarily, trapped in the upper mantle (recent review [11]). Previous numerical models of mantle convection have observed a range of behavior for slabs in the transition zone depending on viscosity stratification and mineral phase transitions, but typically only exhibit flat-lying slabs in the transient state with artificial setting of plate boundary or trench migration is imposed.

We simulated fully dynamical and self-consistent thermal convection in high-resolution 3-D spherical shell models which range up to Earth-like conditions in Rayleigh number, and succeeded in spontaneous generation of plate-like behavior with slab stagnation. We examined the influence of three factors: phase transitions, temperature dependent viscosity with plastic yielding at shallow depth, and viscosity increase in the lower mantle, and clarified the condition for generating stagnant slabs [12]. For the evaluation of the effect of the 660 km phase transition, the regime diagram of convection pattern in an isoviscous mantle is established. It suggests that the present Earth is in the intermittent convection mode. The temperature dependent viscosity with plastic yielding spontaneously produces plate-like behavior with very localized convergence zones at the surface. This plate-like structure can stagnate in the transition zone with the combination of 660 km phase transition and viscosity increase in the lower mantle. The model including these three factors with adequate values generates the coexisting state of stagnant and penetrating slabs around the transition zone (Fig. 5), which are characteristics of mantle convection revealed by seismic tomography. The key mechanism to generate stagnant slabs is the partly decoupled state of the upper and lower mantle flow due to the phase transition.

Acknowledgement

We thank Prof. P. H. Roberts for discussion.

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実地球環境でのマントル・コア活動の数値シミュレーション

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地球のマントルとコアで起こっていると考えられる熱対流は、固体地球に生起するさまざまな活動の根本原因であり、地球の進化を知る上で重要である。コアの熱対流については、計算可能なもっとも低粘性の地球ダイナモモデルをもちいて研究をおこなった。これまでの研究で、粘性パラメータをじゅうぶん低く抑えると、コア表面の温度境界条件が解の性質を大きく変えること、コア表面温度を一定にするような、地球物理的に不適切な境界条件の下では、地球のような強い双極子磁場の生成がさまたげられることを明らかにした。その原因について解析をおこなったところ、温度境界条件がコア内部に吹く西向きの温度風をコントロールし、結果としてトロイダル磁場の生成に影響を与えていることがわかった。地磁気の短時間変動の原因をあきらかにするため､これまでよりも低い粘性パラメータをもちいた数値シミュレーションをおこなった。粘性をあらわすエクマン数と磁気プラントル数はそれぞれ 2.5×10^{-7} および 0.2 である。シミュレーションで再現されるコア表面磁場の西方移動は赤道付近に集中しおり、これは地磁気の特徴とよく似ている。そのメカニズムはコア内部の西向きの温度風によるものと考えられる。しかし位相速度は地磁気のそれよりも著しく遅く、今後さらにレイリー数をあげるなどの必要があろう。さらにコアのねじれ振動に似た振動現象がシミュレーションでも再現されていることをあきらかにした。また地球ダイナモモデルの改良もおこなった。動径方向の空間差分を結合コンパクト差分に置き換えることで、より高い精度が実現されることを確認し、低粘性に起因する薄い境界層の表現に寄与することが期待された。

マントル対流のシミュレーションでは、3 次元球殻において、粘性の温度依存性と浅部での降伏現象、マントル鉱物の相転移、下部マントルでの粘性増加、という 3 つの要素を組み込んで、地球マントルに相当するレイリー数の計算を実行した。その結果、地震波トモグラフィーで見えているような遷移層に滞留（スタグナント）するスラブと突き抜けるスラブとの共存状態が自然に再現されるとともに、表面での沈み込み位置の移動に伴って滞留構造が形成されていく過程を明らかにすることに成功した。滞留構造を生み出す鍵となるのは、負のクラペイロン勾配を持つ相転移により浮力が減じられるため上下マントルの流れが非結合状態になり得ること、そして粘性差により上下マントルに大きな流速の違いが生じること、である。

キーワード: マントル対流, コア対流, 地球ダイナモ, 地磁気永年変化, スタグナントスラブ