Effects of latitudinally heterogeneous buoyancy flux conditions at the inner boundary on MHD dynamos in a rotating spherical shell

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Introduction

A schematic picture of the core dynamics. An example of inner-core flow (Takeda 2011).

Outer core flows, contributing to generation and maintenance of the intrinsic magnetic field of the earth, is considered to be driven by buoyancy caused by the light elements released at the inner core boundary (ICB) through convective condensation of iron and nickel along with the inner core growth.

On the other hand, existence of inner core flows has come to be studied as a candidate of the origin of the anisotropy of seismic velocity in the inner core. (Karato, 1999; Yoshida, 1996; Takeda, 2011)

The typical flow pattern expected in the inner core is axisymmetric and flows are directed from the equatorial region to the polar regions or vice versa.

Since such a flow accompanies mass flux through the ICB, it affects the convective process of iron and nickel, and as a result, latitudinal heterogeneity of the buoyancy (light elements) flux is expected to occur at the ICB.

In the present study, we investigate effects of latitudinally heterogeneous buoyancy flux at the ICB on dynamo process in the outer core through numerical experiments of a 3-dimensional rotating spherical MHD dynamo model.

Methods

System: Bousinesq MHD fluid in a rotating spherical shell $v \cdot \nabla = 0$. $\nabla \cdot B = 0$.

$$E' = (u' \cdot u' - w' \cdot w') + 2\pi r \cdot \nabla P = \nabla \cdot \left( \frac{1}{\mu} \nabla B \right) \times B$$

Variables:
- $u$: velocity.
- $B$: magnetic field.
- $P$: concentration of light elements.

Parameters:
- the modified Rayleigh number $Ra$.
- the Ekman number $E$.
- the Prandtl number $Pr$.
- the magnetic Prandtl number $Pm$.
- the ratio of inner and outer radial boundary conditions.

Boundary conditions:
- No-rotational dynamical condition.
- No-concentrated buoyancy flux at the outer boundary. Latitudinal buoyancy flux is given at the inner boundary.

The typical flow pattern expected in the inner core is axisymmetric and flows are directed from the equatorial region to the polar regions or vice versa.

The outer spherical shell is entitled as the mantle.

Experimental setup

Latiitudinally varying buoyancy (light elements) flux distribution:

$$F_2(r,\theta) = -\left(1 - \frac{2}{3} \sin \theta \right) \left( 1 - \frac{2}{3} \sin \theta \right) \left( 1 - \frac{2}{3} \sin \theta \right)$$

We consider the following three cases:

1. Homogeneous distribution ($\theta = 0$).
2. Strong flux around the equatorial region ($\theta = 0$).
3. Strong flux around the polar region ($\theta = 0$).

Strong flux around the equatorial region ($\theta = 0$).

Strong flux around the polar region ($\theta = 0$).

Strong flux around the equatorial region ($\theta = 0$).

Numerical methods

Traditional spectral transform method.

The temperature and the toroidal/polaroidal potentials of $u$ and $B$ are expanded with spherical harmonic functions in the horizontal directions, Chebyshev polynomials in the radial direction of the shell, and the polynomials developed by Matsushima and Marcus (1994) in the radial direction of the inner sphere.

The time integration is performed with the Crank-Nicolson scheme for the diffusion terms and with the second order Adams-Bashforth scheme for the other terms.

Resolution

The spatial resolution of the model is $32, 64, 32, 24$ grid points in longitudinal, latitudinal, and radial directions in the shell and the inner sphere, respectively.

Spherical harmonics, Chebyshev polynomials and the polynomials by Matsushima and Marcus are calculated up to the 4th, 2nd, and 4th degree, respectively.

Results of non-magnetic convection

$T = 25$.

$T = 25.5$.

$T = 25.15$.

$T = 25.10$.

Discussion

Numerical experiments of compositional convection and MHD dynamo in a rotating spherical shell are performed with strong latitudinal buoyancy flux ($\theta = -1$), strong polar buoyancy flux ($\theta = -2$), and homogeneous buoyancy flux conditions ($\theta = 0$).

In the dynamo calculations, different developments of the magnetic field are observed according to the distribution of buoyancy flux at the inner boundary.

When the homogeneous buoyancy flux is given ($\theta = 0$) strong flux is given around the equatorial region ($\theta = 0$), self-sustained dynamo solutions are obtained for sufficiently large magnetic Prandtl numbers.

However, when strong flux is given around the polar region ($\theta = -2$), all solutions are similar to the magnetic Prandtl numbers in the concerned range of the parameters.

This difference in development of magnetic field is considered to be affected by the different pattern of mean zonal flow.

In the case of strong polar buoyancy flux, direction of mean zonal flow around the inner core moves through the thermal wind balance and strong shear layer is produced.

This shear may stretch the convective columns and present localization of the vortex columns and magnetic field.

Geophysical implications:

It may not be expected that the inner core flows is directed from the polar regions to the equatorial region, because such a buoyancy flux pattern may be unfavorable for development and maintenance of the strong geomagnetic field.

Future investigation of in broad range of the parameter space is needed, since the values of the parameters which lead to the present study are quite different from those of the real central core of the earth.

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The numerical codes used in this present study is also available from the SPOMODEL MHD DynoR package: http://www.gfd-lab.org/software/DynoR/

The products of the Demon-Ruby project were used to draw the figures: http://www.gfd-lab.org/software/Ruby/

References


