Effects of thermal boundary conditions on geodynamo with various Rayleigh numbers and inner core radii

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The Earth has been sustaining its intrinsic magnetic field for at least 3.5 billion years as revealed by paleomagnetic studies [e.g., Biggin et al., 2015]. The geomagnetic field is generated and maintained by dynamo action due to convection of liquid iron alloy in the outer core. Studies of the thermochemical evolution of the Earth's core suggest that the solid inner core has been growing up for approximately one billion years [e.g., O'Rourke and Stevenson, 2016]. Consequently, heat flow in the core has also been changing through the Earth's history [e.g., Driscoll and Bercovici, 2014]. Hence it is important to investigate dynamo condition on heat flux with various inner core size to understand environment of the past Earth. There are some numerical dynamo simulations focusing on the various inner core size. Heimpel et al. (2005) evaluated dynamo onset conditions with various inner core size for fixed temperature boundary. Hori et al. (2010) found that magnetic field is more dipolar on the fixed heat flux boundary condition rather than on the fixed temperature boundary condition for two cases of different inner core size. A thermal evolution model suggests that geomagnetic field has been dipolar for recent 0.6 billion years [Driscoll, 2016]. Lhuillier et al. (2019) point out that magnetic field is less dipolar when the ratio of the inner to outer core radii, r_i/r_o, ranges between 0.2 and 0.22. However, it is still unclear how different inner core size influences the mechanism of generating dipolar or non-dipolar field.

In the present study, we investigate the effects of the thermal boundary conditions on numerical dynamos with various inner core size using a numerical dynamo code Calypso [Matsui et al., 2014]. We fix the Ekman, Prandtl, and magnetic Prandtl numbers to be $E = 10^{-3}$, $Pr = 1$, and $Pm = 5$, respectively, and change the Rayleigh number (Ra) and the ratio of inner to outer core radii to be $r_i/r_o = 0.15$, 0.25, and 0.35. We set two boundary conditions; (FT case) fixed temperature at the inner core boundary (ICB) and at the core-mantle boundary (CMB), and (FF case) fixed heat flux at the ICB and at the CMB. We calculate dipolarity (f_{dip}) to evaluate the ratio of the axial dipole component to total components and the Elsasser number (Λ)to investigate how strong the Lorentz force is against the Coriolis force.

The results of numerical simulations carried out in the present study are summarized in Table 1 and Figure 1. The range of Ra/Ra_{crit} (Ra_{crit} is the critical Rayleigh number) for $\Lambda >> 1$ are listed in Table 1, which indicates that the range for FF case is narrower than that for FT cases. Figure 1 shows the dipolarity as a function of Ra/Ra_{crit}. The Ra dependence of f_{dip} for $r_i/r_o = 0.25$ is similar to that for $r_i/r_o = 0.35$ in FT case, whereas f_{dip} has different behavior between $r_i/r_o = 0.25$ and 0.35 in FF cases.

In $r_i/r_o = 0.35$, f_{dip} in FF case decreases more rapidly with increasing Ra than that in FT cases. In large Ra cases, an axial component of magnetic energy is dominant in FT while the axisymmetric magnetic energy is small in the FF cases.

In $r_i/r_o = 0.25$, f_{dip} is larger than 0.55 in all Ra range where Λ is much larger than 1 in FT, but is larger only in $Ra/Ra_{crit} = 1.9$ in FF. In large Ra cases, difference of f_{dip} between FT and FF cases is smaller in $r_i/r_o = 0.25$ than in $r_i/r_o = 0.35$. Different from $r_i/r_o = 0.35$, the axisymmetric magnetic energy is dominant in all FT and FF cases.

In $r_i/r_o = 0.15$, dipolar dominancy is weak while the Lorentz force is not small in large Ra in FT cases. In these cases, although convection is intense, magnetic field is concentrated in one of anti-cyclonic columns. This kind of dynamos only exist in $r_i/r_o = 0.15$. In FF cases, magnetic field is not sustained in

large *Ra*. Dipolar field is sustained in small *Ra* range for $\Lambda >> 1$.
The common dependency on the inner core size in FT and FF is that dipolar dynamos are difficult to occur with the smaller inner core. FF cases are more difficult to sustain dipolar dynamos than FT cases. For considering the Earth's heat history, we need further simulations with larger heat flow on CMB than on ICB to take into account of the cooling process of the outer core.

Keywords: geodynamo, the Rayleigh number, inner core size, past Earth, dipolarity, the Elsasser number

Table 1 The Ra/Ra_{crit} range where Λ is much larger than 1.

$r_{\mathrm{i}}/r_{\mathrm{o}}$	FT	FF
0.15	$10.1-15.6$	$8.1-8.9$
0.25	$2.2-3.1, 4.6-5.0$	1.9
0.35	$2.0-6.1$	$2.7-3.8$

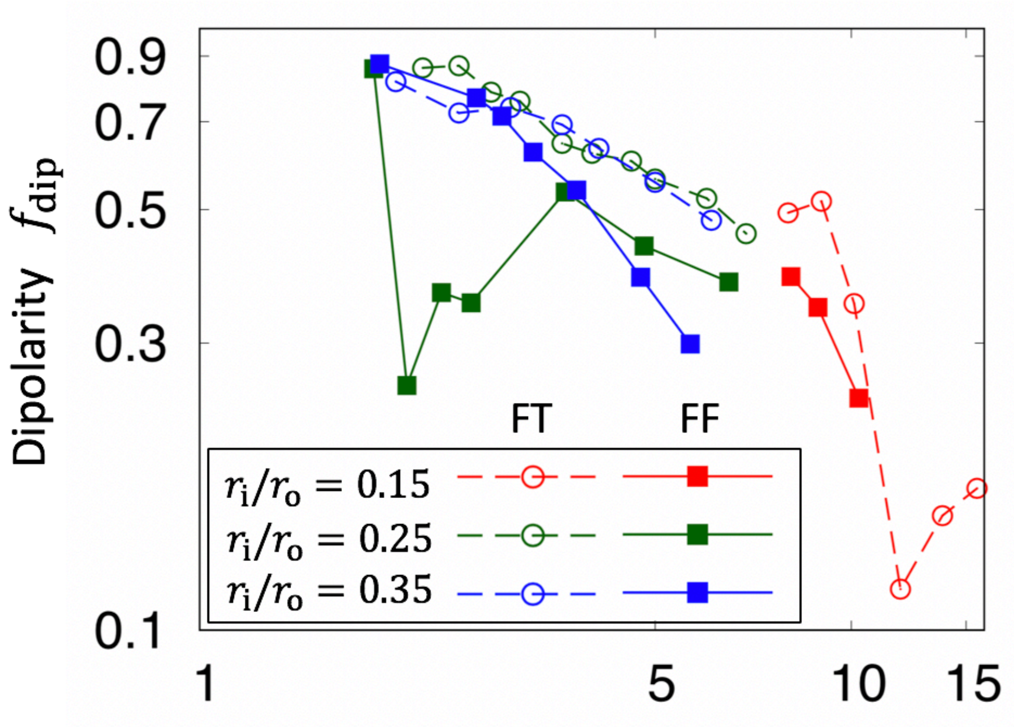

Figure 1 Dipolarity as a function of Ra/Ra_{crit}.