Response to **Interactive comment on "A simple 3-D numerical model of thermal convection in Earth's growing inner core: on the possibility of the formation of the degree-one structure with lateral viscosity variations" by M. Yoshida**
S. Zhang (Referee)

Although this isn't exactly my area of expertise, I do find the topic of this paper interesting. Degree-one like inner core structure has been proposed by recent seismological studies. This paper carried out a series of 3D thermal convection simulations to explore the possibility of generating this kind of structure by an "endogenic factor". While exploring the major uncertainties of the model parameters such as rheology and the thermal conductivity of the inner core, the author concludes that an "endogenic factor" is less probable. The lateral viscosity variation considered here is a good addition to previous works, and this improves our understanding of the core evolution, which is worth publishing. However, the numerical treatment borrowed directly from mantle convection simulations requires a few changes to be suitable for inner core convection. And some details of those treatments carried out in this paper are oversimplified or improper to me (listed below). I would like to suggest some corrections or justifications before the paper can be published.

[Reply] I sincerely thank the reviewer for constructive comments. I have carefully incorporated all the comments and suggestions into the revised manuscript attached below. The revised parts are highlighted by red. I provide below my response to reviewer's comments.

Some detailed comments are listed below:

1. This study uses mantle convection simulations to deal with convection within a growing inner core. In contrast to mantle convection studies, the author uses a timedependent inner core radius to get dimensionless equation Eq. (2-4) to account for a growing inner core. However, the Eq. (2-4) is build based on an Eulerian specification that is fixed on space. With a growing inner core radius, the grid is actually slowly expanding through time. So strictly speaking, mass, momentum, and energy are no longer conserved with this expending mesh. One could argue that the growth rate is small enough to make it negligible, and there are also some previous studies using a similar treatment. However, considering the significant accumulating growth of the inner core during the whole simulation, I still feel this requires some improvement or at least a more detailed justification.

[Reply] Thank you for your comment. I agree with your comment. The framework of present model is based on mantle convection simulations to deal with convection within the growing inner core. In contrast to mantle convection simulations, I used a time-dependent inner core radius to get dimensionless equations Eq. (2–4) to account for the growing inner core. However, Eq. (2-4) is build based on an Eulerian specification that is fixed on space. With increasing inner core radius, the grid is actually slowly expanding through time. Thus, strictly speaking, mass, momentum, and energy may be no longer conserved with this expending grid, although the growth rate could be small enough to make it negligible. However, considering the significant accumulating growth of the inner core during the whole simulation, improvement of the present numerical model should be required. I openly discussed this problem in Section 4.

2. p. 3820, l. 12-14. As the small sphere is imposed, it created an additional inner boundary, what's the boundary condition here? And how is it made consistent with reality? The temperature difference across the inner core seems to be constant during the whole simulation. What is the justification for that? As the inner core radius grows significantly through time, and it cools as well, I don't see any particular reason that this will stay almost the same.

[Reply] About the boundary condition, impermeable, shear-stress-free, adiabatic conditions are imposed on the top boundary of the small virtual-sphere for the purpose of technical convenience. However, this is just for the purpose of computational convenience, and this setup does not mean the existence of the real singularity that violates the mass and heat transport near the center of the model sphere. This is explicitly explained in Section 2. And, about the temperature difference across the model domain, I ignore the secular cooling of the whole inner core, because the cooling rate and the resulting time change of the temperature difference across the inner core can not be estimated a priori. However, the absolute time change in the temperature difference across the inner core should be small throughout the inner core formation, and the effect of the time change on the magnitude of thermal Rayleigh number (Eq. 5) is negligibly small compared to other physical values. Therefore, I consider that this assumption would be justified at least in the framework of this numerical model. I explicitly explained this point in Section 2.

3. Ep.(8) and p.3823, l. 1-4 "The heat source associated with solidification of the inner core are ignored because these effects play a secondary role in the growth of the inner core (Buffett et al., 1992)". This isn't correct. Buffett et al., (1992) keeps the latent heat and gravitational energy terms in their equation, and most other research keep them as well. For example, in core evolution models from Gubbins et al. (2003), Nimmo et al. (2004), the latent heat plus gravitational energy is larger than the specific heat term for present day Earth. These research also show once the inner core starts to freeze, the core temperature dropping rate decreases significantly. So this isn't a secondary effect that can be ignored.

[Reply] Thank you for your comment. Following your comment, I removed this sentence and modified based on new references below:
- Gubbins, D., Alfè, D., Masters, G., Price, G.D. & Gillan, M.J., 2003. Can the Earth's dynamo run on heat alone?, *Geophys. J. Int.,* **155**, 2, 609-622, doi:10.1046/j.1365-246X.2003.02064.x.
- Nimmo, F., Price, G.D., Brodholt, J. & Gubbins, D., 2004. The influence of potassium on core and geodynamo evolution, *Geophys. J. Int.,* **156**, 2, 363-376, doi:10.1111/j.1365-246X.2003.02157.x.

Although Buffett et al. (1992) implicitly evaluated that these effects play a secondary role in the growth of the inner core, most of other studies kept these effect. For example, the modeling studies of the core evolution by Gubbins et al. (2003) and Nimmo et al. (2004) revealed that the latent heat plus gravitational energy is larger than the specific heat for the present Earth, and once the inner core starts to freeze, the core temperature decreases significantly with time, which has probably influence on the growth speed of the inner core and the generation and maintenance of geodynamo. I explicitly discussed this point in Section 2.

4. The gravity acceleration seems to be treated as a constant in this study. Different from the mantle, the gravity acceleration should be almost linearly increasing from 0 at the centre to _4.4 m/sˆ2 at the present day ICB (e.g. PREM model). I would expect depth dependent g will have some influence on the convection that should be considered.

[Reply] Yes, I treated it as a constant with radius in this model for the simplicity. I explained explicitly this point in Section 2.

5. Although model uncertainties of CMB heat flow and inner core age are mentioned in the discussion, the heat flow is assumed to be constant in this study. Moreover, only low CMB heat flow and a slowly growing inner core with an age of _4.5Gry are tested in this study, which are extreme cases rather than “realistic” ones. As mentioned in the discussion of this paper, there are many studies that suggest larger CMB heat flow and younger inner core age. And the CMB heat flow may have a significant variation through the whole Earth’s history. Whether the fast growing inner core leads to a different flow pattern or not needs to be explored. So, I would like to suggest an additional test model with fast growing inner core.

[Reply] According to a more recent paleogeomagnetic study, the inner core formed at ~1.5 Ga (Biggin et al. 2015). This “young” inner core age is consistent with the indirect evidences from seismology and mineral physics that the CMB heat flow is larger than previously thought (Hernlund et al. 2005; Lay et al. 2006; van der Hilst et al. 2007). In the present numerical model, the CMB heat flow is assumed to be constant, Fm’ = 2.56×1012 W, based on the model constants used in Buffett et al. (1992) and the initial radius of the inner core arbitrarily set. As stated in Section 2, this value would be a lower limit value for the present Earth considering an even relationship between the total plume buoyancy flux observed at the Earth’ surface and the inferred total CMB heat flow (e.g., Davies 1988; Sleep 1990; Davies & Richards 1992) and a minimal power requirement for maintenance of the geodynamo (Buffett 2002). However, the CMB heat flow in the past Earth would be lower than that in the present Earth, because the average mantle temperature may increase as the Earth older. More than that, there is a possibility that the CMB heat flow may have a significant variation throughout the Earth’s history. Although the implementation of time-dependent CMB heat flow is beyond the framework of the present simple numerical model, it might be a serious problem for the growing speed of the inner core. However, if the inner core grows faster than the present model, the degree-one structure would only appeared for a further limited range of viscosity contrast of temperature dependence than the results presented in this paper. Therefore I believe that the conclusion on the less possibility of an endogenic origin for the degree-one thermal/mechanical structure of the inner core is justified. I discussed this point explicitly in Section 4.

Technical correction:

p. 3821, l. 15 “g” should be g0

[Reply] Fixed.

I hope these comments/suggestions will be found useful by the author when preparing a revised version of the article.

[Reply] I again deeply appreciate you for the careful reading and significant improvement of this paper.

Masaki Yoshida