Thermal convection in the mantle of super-Earths

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Thermal convection in the mantle of super-Earths is one of the most important issues to understand their thermal history and surface environment. It is also linked to the habitability of planets because it controls the plate motion, material circulation, the vigor of core convection and planetary dynamos, and so on.

One of the most important differences between the Earth's and super-Earth's interior is that there is a strong adiabatic compression effect in super-Earths. Usually, this effect is ignored in modelling the dynamics in the mantle of the Earth because the effect is small in the Earth. However, this effect becomes strong as the size of planets increases so it cannot be ignored in large planets. In this paper we introduce our results of numerical simulation studies of thermal convection in super-Earths (up to ten times the Earth's mass) with this effect (Miyagoshi et al., 2014; 2015; 2017; 2018). We also take account for high Rayleigh number which is relevant for super-Earths, and temperature-dependent viscosity contrast and depth-dependent thermal expansion coefficient.

We found that the activity of ascending hot plumes is lowered as the planetary size increases. In contrast, the activity of cold plumes is not lowered even in large planets. The efficiency of heat transport by thermal convection is significantly lowered compared with the results with Boussinesq approximation in which there is no adiabatic compression and which is often used in models for the Earth. We also found the convective regime diagram in massive super-Earths (ten times the Earth's mass) and how the threshold between stagnant-lid regime and weak-viscosity-contrast regime is determined.

We also found the effects of adiabatic compression become substantial when the planetary mass exceeds about 4 times the Earth's mass. The plate thickness increases and the convective velocity is almost constant as the planetary mass increases. These results are in a striking contrast with earlier predictions that are made by the Boussinesq approximation models.

We also explored the thermal evolution process in massive super-Earths (ten times the Earth's mass). At initial the shallow mantle of the planet is hotter than expected from the adiabatic extrapolation from the deep mantle, as expected when the planet is formed from giant impact. We found that the influences of an initial temperature distribution continue extremely long in massive super-Earths. In our case, transient layered convection caused by the initial temperature distribution continues for as long as several to ten billion years before it yields to a whole layer convection.

Our results suggest that the tectonic activities such as plate motion and hot spot volcanisms hardly occur as planetary size increases. The planetary magnetic field is expected to be not so strong in massive super-Earths because of the weak efficiency of heat transport by the mantle convection. In addition, especially in massive super-Earths, special attention for the extremely long transient stage which is affected by the initial temperature distribution is necessary to discuss details of its interior and tectonic activities.

Keywords: super-Earths, mantle convection, adiabatic compression

