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Thermal convection of compressible fluid in the mantle of super-Earths

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ABSTRACT

To understand how adiabatic compression influences mantle convection in super-Earths, we carried out linear stability analysis and non-linear numerical simulation of thermal convection for constant viscosity infinite Prandtl number fluid with both constant and pressure-dependent thermal expansivity. The mantle is basally heated and internal heating is not considered. In the case of constant thermal expansivity, thermal convection is totally inhibited in super-Earths of more than about 5 times the Earth's mass owing to the strong effect of adiabatic compression, when the surface temperature is sufficiently high. Pressure-dependence of thermal expansivity is crucial for the onset of convection in massive super-Earths. Even when the thermal expansivity depends on pressure, our numerical simulation shows that the effect of adiabatic compression reduces the efficiency of convective heat transport by up to about 60%, depending on the planetary mass and the surface temperature. The reduction in the efficiency of convective heat transport makes cooling of the mantle more difficult in massive super-Earths, especially when the surface temperature is high. The surface temperature of a planet may affect its thermal history not only through its effects on the mechanical properties of convecting mantle materials, but also through its influence on adiabatic compression of convecting materials.

1. Introduction

Since the first discovery of extra-solar planet (Mayor and Queloz, 1995), the rapid improvements of observational instruments and techniques have enabled detection of extra-solar planets of super-Earth size (Udry et al., 2007). Some of the detected planets are found to have low mass (up to 10 times the Earth's mass) and high density (more than 5000 kg/m^3), and the Kepler mission reported detections of additional large number of super-Earth candidates (Borucki et al., 2011). The high mean density of these planets suggests that the interior of these planets consists of silicate mantle and iron core like the Earth (Valencia et al., 2010). These discoveries have stimulated studies of mantle dynamics expected in the super-Earths. Here, we investigate how the large mass and size of super-Earths affects the sub-solidus thermal convection expected in their mantle by linear stability analyses and simple numerical experiments.

Many of earlier studies on dynamics of the mantle in super-Earths focus on clarifying whether or not plate tectonics operates on these planets. From studies of the mantle convection in the Earth, Solomatov (1995) and Moresi and Solomatov (1998) suggest that plate tectonics operates when mantle convection that occurs beneath the lithosphere induces stress higher than the rupture strength of the lithosphere by basal drag. Based on this criterion and a simple scaling law of mantle convection or numerical simulations, Valencia and O'Connell (2009), van Heck and Tackley (2011) and Korenaga (2010) suggest that plate tectonics becomes more likely with increasing planetary size. Korenaga (2010) and van Heck and Tackley (2011), however, suggest that the effect of large planetary size is secondary, and that the presence of water that reduces the mechanical coupling at plate boundaries is more important for inducing plate tectonics in super-Earths. In contrast, Foley et al. (2012) suggest that plate tectonics operates when the viscosity contrast between the lithosphere and the asthenosphere is below a threshold, based on their damage parameter model of plate tectonics. They suggest that the threshold significantly increases with increasing planetary size, and conclude that plate tectonics is definitely likely in super-Earths.

Besides its effect on plate tectonics, the large mass and size of super-Earths has been suggested to affect mantle convection through its effect on mantle viscosity. Karato (2011) suggests that viscosity decreases, rather than increases as commonly believed, with increasing pressure in deep mantle of super-Earths owing to the very high pressure there. Stein et al. (2011) suggest that this pressure weakening induces stress decoupling between the lithosphere and deep interior, and that plate mobility decreases with increasing planetary size. Stamenkovic et al. (2011), however, suggest that the higher pressure in deep mantle of super-Earths makes

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the viscosity higher there, based on their thermodynamic calculations of mineral properties. The higher viscosity would affect the thermal history of super-Earths, which has been studied by the use of parameterized convection models (Papuc and Davies, 2008; Tachinami et al., 2011). The effects of pressure-dependence of mantle viscosity under very high pressure on mantle convection in super-Earths are still an open issue.

In these studies on possible plate tectonics and thermal history in super-Earths, however, the effect of adiabatic compression on mantle convection has not drawn much attention. Jarvis and McKenzie (1980) carried out linear stability analyses and non-linear numerical simulations of finite amplitude thermal convection of compressible, infinite Prandtl number fluid in two-dimensional space. They found that the density stratification due to adiabatic compression greatly enhances the convective stability of the mantle when the depth of the mantle far exceeds the thermal scale height. Bercovici et al. (1992) obtained the same result for thermal convection in three-dimensional spherical shell. Additionally, they found that compressibility has a significant effect on the spatial structure of steady convection when the super-adiabatic temperature-drop across the shell is much smaller than adiabatic temperature drop. If the effect of adiabatic compression on the onset of thermal convection is so strong as suggested in these studies, it is necessary to first ask whether or not mantle convection can occur before asking whether or not plate tectonics operates in super-Earths. In this study, we carry out a series of linear stability analyses and non-linear numerical simulations for thermal convection of compressible fluid to understand the effect of adiabatic compression on the onset of thermal convection and the efficiency of convective heat transport in the mantle of super-Earths.

2. Model description

To understand mantle convection in super-Earths of various mass, we carry out both linear stability analyses and numerical simulations of thermal convection of an infinite Prandtl number fluid under the anelastic approximation (e.g. Jarvis and McKenzie, 1980). The geometry of the convecting vessel is two-dimensional Cartesian; the vessel extends infinitely in horizontal direction in the linear stability analyses, while is a rectangular box of aspect ratio 4 in the numerical simulations. The convecting vessel is heated from below, and there is no internal heat source. The viscosity is constant. We examine both constant and depth-dependent thermal expansivity cases. The temperature at the surface and the bottom boundaries are fixed at T_s and T_b, respectively. All of the boundaries are shear stress free and impermeable.

2.1. The hydrostatic state

The pressure $\hat{p}$ and the density $\hat{\rho}$ are split into the hydrostatic parts $\bar{p}(z)$ and $\bar{\rho}(z)$, respectively, and their deviations:

$$\hat{p} = \bar{p}(z) + p, \tag{1}$$

$$\hat{\rho} = \bar{\rho}(z) + \rho = \bar{\rho}(z)(1 - \alpha T), \tag{2}$$

where z is the depth, α is the thermal expansivity, and T is the temperature. For the hydrostatic parts, we assume simple linear dependences on depth z, based on earlier models of mantle-structure (Valencia et al., 2006):

$$\bar{\rho}(z) = \rho_0 + \rho_0(1.75M_p^{0.258} - 1)(z/d); \tag{3}$$

$$\bar{p}(z) = (127.4M_p + 7.241)(z/d)[\text{GPa}]. \tag{4}$$

Here, d is the depth of the mantle, the planetary mass M_p is normalized by the Earth's mass, and ρ_0 is the reference density.

The use of Eqs. (3) and (4) implies that we study the mantle of an Earth-like planet, as Valencia et al. (2006) assume. More specifically, we assume that the mass fraction of the core to the planet and the composition of the mantle are Earth-like. For super-Earths with different mass fraction of the core, etc., the scaling laws would become different from the one expressed by Eqs. (3) and (4). We make this assumption simply to fix the model: The issue addressed here is to show the overall picture of how adiabatic compression affects mantle convection, and detailed estimates of the influence of adiabatic compression for a specific super-Earth is beyond the scope of this paper. Strictly speaking, Valencia et al. (2006) also assume a temperature-distribution in the mantle based on a simple parameterized convection model, which is not consistent with the temperature-distribution we will calculate below. The inconsistency is, however, not important because of the weak dependence of the interior structure of planets on temperature. The scaling laws depend on the equation of state (EoS) that is assumed for the mantle and the core materials, too. The dependence is, however, negligible as can be inferred from the difference between the scaling law based on the EoS of Valencia et al. (2007) and that based on the EoS of Wagner et al. (2011), which are less than 2%. In addition to the assumptions contained in Valencia et al. (2006), we make further simplification: We neglect various high-pressure induced phase transitions, and fitted Eq. (3) to the overall density-profile calculated in Valencia et al. (2006); the effects of phase transitions on mantle convection in super-Earths are an issue that deserves a separate work. We also fit a linear function of Eq. (4) to the hydrostatic pressure calculated from Eq. (3) and the gravitational acceleration that corresponds to the interior structure of Valencia et al. (2006).

The thermal expansivity α in Eq. (2) depends on pressure, and this pressure-dependence has a profound influence on mantle convection in super-Earths as we will show below. Table 1 and Fig. 1 show the pressure-dependent thermal expansivity assumed here; a linear interpolation scheme is used in the figure to calculate α at pressures between the values shown in Table 1. The estimate of α is made for MgO, a major constituent of mantle minerals, by an *ab initio* calculation (Tsuchiya, personal communication). In the figure, we also present earlier estimates of α for MgO (Chopelas and Boehler, 1992) and SiO_2 (Tsuchiya and Tsuchiya, 2011; Wang et al., 2012) at various temperatures and pressures. Though the earlier estimates are sparse, especially at $\bar{p} > 100$ GPa, the pressure-dependent α assumed here is consistent with these estimates. In particular, the rapid decrease in α with increasing $\bar{p}$ in the range of $\bar{p} < 100$ GPa is a feature that is well established from earlier laboratory experiments (Schubert et al., 2001). Fig. 1 suggests that the thermal expansivity is about 1/20 of its surface value at the base of the mantle in a planet with a mass ten times that of the Earth, and that the temperature and compositional dependences of α are secondary to its dependence on pressure. To elucidate the important role that this pressure-dependence plays in mantle convection,

Table 1
The assumed pressure dependence of the thermal expansivity.

Pressure (GPa)	Thermal expansivity (10^{-5} K^{-1})
0	4.0
10	3.5
30	2.6
60	1.86
100	1.38
150	1.10
300	0.701
600	0.3764
1000	0.3034
1500	0.2587