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Mantle convection in super-Earths with high compressibility, high Rayleigh number, and temperature-dependent viscosity

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Understanding mantle convection in super-Earths is a key to clarifying their habitability, because mantle convection determines the surface environment and the magnetic field intensity through the influence on the activity of core convection. The large size of super-Earths implies that the depth of their mantle far exceeds the thermal scale height. In this paper, we present numerical simulation results of mantle convection in super-Earths with high compressibility, high Rayleigh number, strongly temperature-dependent viscosity and depth-dependent thermal expansivity.

Thermal convection of compressible infinite Prandtl number fluid is solved in a rectangular box under anelastic approximation by the ACuTEMAN (Kameyama et al. 2005). The model of the super-Earths, including depth-dependent thermal expansivity and density, is the same as Tachinami et al. (2013, submitted). The dissipation number is 5, which corresponds to terrestrial planets of ten times the Earth's mass. The Rayleigh number defined with the viscosity at the core-mantle boundary (CMB) Ra is from 6E6 to 1E10. A viscosity contrast r up to 1E7 arises between the CMB and the surface owing to the temperature-dependence of viscosity. The employed grid number is 1024 (horizontal) and 256 (vertical).

Numerical results show that the efficiency of heat transport by the mantle convection in super-Earths becomes smaller than that in the Earth owing to adiabatic compression effect. For example, at Ra=1E10 and r=1E3, the Nusselt number is only about twenty, less than the expected value when the effect of adiabatic compression is neglected. This low efficiency of heat transfer strongly affects the evolution of the super-Earths. The magnetic field of super-Earths, for example, is probably weak because the core is not cooled efficiently. The weak magnetic field can be fatal for the habitability of super-Earths. We also found that in some cases it takes time longer than the age of the Universe for the calculated mantle convection to go through with the initial transient stage. This suggests that the initial transition stage, not the statistically steady stage, is more relevant to most of the time in the evolutionary history of super-Earths. The temperature and flow field show that at high Ra and at strong temperature-dependent viscosity the stratosphere develops in the middle of the mantle. Hot plumes from the CMB does not ascend to the surface of the planet. Cold plumes that grow at the base of the lithoshere are weak or are totally inhibited by the strong effect of adiabatic compression. The thermal structure of the mantle in super-Earths is totally different from that of the Earth.

Keywords: mantle convection, super-Earths